

# INTERPRETING SOIL TEST RESULTS

WHAT DO ALL THE NUMBERS MEAN?

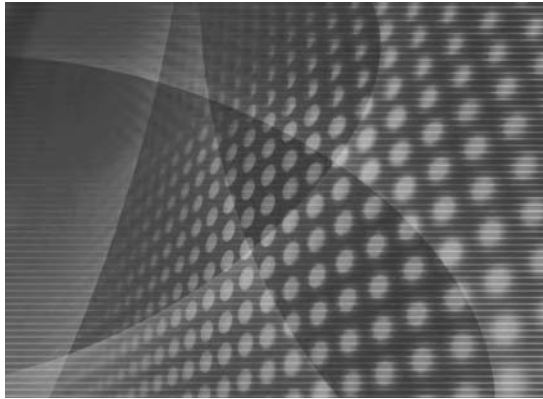
PAM HAZELTON AND BRIAN MURPHY

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# Foreword

At the University of Adelaide (and I imagine it is the same at all Australian universities) we get regular requests from students and others (mainly advisers and consultants in soil management) for advice on how to interpret soils data. Typically, we get inquiries about soil-test results obtained from fertilizer companies, engineering reports on clay reactivity, heavy-metal concentrations in municipal and industrial waste-products, bore- and dam-water analyses, soil water contents and hydraulic conductivities. The units accompanying such data invariably appear as a dog's breakfast of the *Système International* mixed with colloquial names dating back to the early 20th century (e.g. bags, bushels, quintals, milliequivalents, etc). Naturally, people ask whether a good Australian textbook exists 'to guide us through the minefield of numbers we face out there'. Well, here it is – a friendly book containing exemplar tables and units with plenty of explanatory text to guide you through the quagmire of colloquial terms in soil science that we need to extricate ourselves from. This omnibus reference-text falls between a classical methods manual and a book of results with typical generalisations to be drawn from them. It gives users of soil data some yardsticks up against which the significance or importance of the numbers they obtain in standard soil tests can be assessed. For many users of Australian soils data this book will come as a lifeline, and we will certainly add it to the reading lists for our students.

Drs Cameron Grant and Jock Churchman  
Australian Society of Soil Science Inc. Publications Committee



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# About the authors

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Dr Pam Hazelton has worked as a soil scientist for 35 years. She graduated in Science from the University of Sydney; gained a Diploma of Education from the University of New England and a PhD from the University of NSW for her work on the morphology and genesis of scald soils in arid regions. She is an experienced pedologist, having produced many Western Division land system maps and also soil landscape maps in the south-eastern areas of New South Wales. In recent years her interests have been in coastal and urban land use with an emphasis on environmental engineering. She lectures in the Faculty of Engineering in the Infrastructure and Environmental Group at the University of Technology, Sydney as well as in Hong Kong and in France.

# Preface

The first edition of this text, originally titled *What Do All the Numbers Mean?*, was written specifically for officers in the then Soil Conservation Service of NSW, who were expected to interpret and provide advice on a wide variety of soil management issues that occurred in their areas. There was no comprehensive text available that could help them with that task. In this second edition, *Interpreting Soil Test Results: What do all the numbers mean?*, the information in the original publication has been reviewed and revised. The data contains test results that are more wide reaching than ever originally intended. The text is, therefore, useful for a wider range of professionals from agriculturists to engineers. The data collected from numerous sources also highlights the large volume and diversity of information needed by all professionals who endeavour to provide advice on natural resource management. The interpretations and values provided in this text are not intended for specific advice on particular problems or issues, but provide a general background on the variety of soil tests available and how the results from these tests may be interpreted. In this second edition a reading list has been included in the appendix for those professionals who need further clarification when working in specific subject areas.

## Disclaimer

The interpretations of soil test results in this book are to be used as a general guide only. They are not to be used in relation to any specific site. An individual site can only be assessed following investigation and interpretation of the soil tests relating to that site. The State of New South Wales, the NSW Department of Natural Resources, and the University of Technology, Sydney, and their employees, officers, agents or servants are not responsible for the result of any actions taken on the basis of the information in this book, nor for any errors, omissions or inaccuracies in this book. The State of New South Wales, the NSW Department of Natural Resources, and the University of Technology, Sydney, and their employees, officers, agents or servants expressly disclaim all and any liability and responsibility to any person in respect of anything and of the consequences of anything done or omitted to be done by any such person in reliance, whether wholly or partially, upon the information in this book.

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# Introduction

Soils are a valuable resource and a critical component in many of the environmental and economic issues facing today's society. Understanding soils and interpreting soil data is especially relevant for many environmental and land management issues facing the community. These issues include urban development, control of salinity, clearing of native vegetation, prevention of land degradation, control of water and wind erosion, irrigation development, the management of effluent disposal and the management of acid sulfate soils.

However, soil science is a specialised field and can be complex. When writing or examining land assessment or environment reports it is often difficult and time consuming to find interpretation of the soil data. These guidelines were compiled to assist in overcoming this problem and are designed for workers in all categories of land use management. The information in this book was collated from a wide range of reference material.

The interpretations and values provided in this text are not intended for specific advice on particular problems or issues, but provide a general background on the variety of soil tests available and how the results from these tests may be interpreted. They are not intended to be used as a replacement for specific professional advice.





# Soil sampling

## 1.1 Where, how and when to sample

To characterise soils at a site, a suitable sampling design is required. Sampling design depends on:

- the landscape or location from which samples are being taken
- the purpose for which samples are being taken
- the resources available to take and test the samples.

The basic questions to be considered are:

- When is the best time to sample?
- Where should the soil be sampled?
- How many samples are required?
- What spatial pattern should be used to take the samples?
- What depths should be sampled?

For general sampling purposes, the basis for making these decisions is discussed in Petersen and Calvin (1986), Beattie and Gunn (1988), Rayment and Higginson (1992), McBratney (1993), Brown (1999), and Chapman and Atkinson (2007). If contaminated sites are to be sampled then there are some special problems in sampling soils. These need to be taken into account to ensure that the samples are representative of the site. These problems are discussed in Laslett and McBratney (1995).

However, there are some general sampling patterns that are frequently used, including:

- regular grid
- regular transect (often used when there is thought to be a trend in a particular direction)

- completely random
- stratified sampling where samples are taken on the basis of:
  - landforms
  - sections of a paddock, especially if a paddock has different soils or landform elements within it
  - areas of different management histories
  - some other stratifying factor
- stratified random sampling, where the samples within each stratifying unit are randomised
- herring-bone grid (for contaminated sites).

Once collected, samples for nutrient analyses may be bulked to give a composite sample. Generally, bulking should be done only when the samples come from a relatively uniform area, or what is thought to be a relatively uniform area. Petersen and Calvin (1986), Tiller (1992), McBratney (1993), and Laslett and McBratney (1995) discuss the limitations of bulking samples and the recommended procedures to follow.

Another difficulty in sampling is the problem of temporal viability, where results for samples or measurements taken at one time may be different to results for samples or measurements taken at another time. Some obvious examples are:

- Measuring infiltration in a tilled paddock. The infiltration is much higher before rainfall packs the soil down and crusts the surface.
- Measuring salinity on a site after a large amount of rainfall. After rainfall the soil solution may be diluted, compared with the solution measured after a dry period.
- Sampling soils immediately after adding fertiliser or soil ameliorants such as lime or gypsum.

These difficulties need to be considered when sampling soils or making measurements on soils and when interpreting the results of any tests carried out. Sampling through time is required, or, alternatively, the conditions when measurements are made or samples are taken should be standardised (or at least recorded). For example, some soils require specialised sampling techniques such as the following:

- For best practice sampling procedures for acid sulfate soil refer to Ahern *et al.* (1998, 2004) and subsequent version updates as they occur.
- Sampling soils for rapidly metabolised chemical species such as nitrate ( $\text{NO}_3^-$ ) (see Peverill *et al.* 1999).

## 1.2 The number of samples required to produce a soil map

The number of samples or ground observations needed to produce a soil map or to do an investigation will vary with the local characteristics of the site. Factors that influence the number of samples required include:

- geology
- landform

- land use history
- purpose for which the investigation is being done.

There are general guidelines on the number of samples required to produce a reliable map (Reid 1988). It should be remembered that these are general guidelines and their applicability will be influenced by the factors outlined in Section 1, Soil Sampling. The number of samples required is usually expressed as the number of samples or observations per cm<sup>2</sup> of the map (see Table 1.1).

**Table 1.1.** Number of observations for 1 km<sup>2</sup>  
(1 km<sup>2</sup> = 1000 × 1000 m)

Scale	Recommended range		Minimum acceptable range
	at density of 1 cm <sup>-2</sup> of map	at density of 0.5 cm <sup>-2</sup> of map	at density of 0.25 cm <sup>-2</sup> of map
1:5000	400	200	100
1:10 000	100	50	25
1:25 000	16	8	4
1:50 000	4	2	1
1:100 000	1	0.5	0.25
1:250 000	0.16	0.08	0.04
1:500 000	0.04	0.02	0.01

Source: Reid (1988).

Tables 1.2–1.3 are a general guide to the minimum number of samples required for 1 km<sup>2</sup> of land at different map scales. Different criteria apply for investigations of areas less than 1 km<sup>2</sup>.

The relationship between soil survey effort and map scale has been derived by Dent and Young (1981). It estimates the effort required in days in the field to develop a soil map at different scales. The actual effort will vary depending on such factors as existing information, the complexity and predictability of the soil patterns and difficulties of access. Nor do these estimates consider the purpose for which a soil map is being developed. Nor do they take account of modern methods of soil survey using remote sensing and geographic information systems (Gunn *et al.* 1988; Gessler *et al.* 1995). They are intended to indicate the relative effort required for a detailed soil map at the scale and thus represent a maximum value. Therefore, these are only broad guidelines.

**Table 1.2.** Recommended intensities of investigation based on map scale (DLWC 2000)

Scale	Area shown by 1 cm <sup>2</sup> of map	Typical land use types	Site and soil observations	Site and soil profile descriptions	Profiles with laboratory analyses
1:100 000	100 ha = 1 km <sup>2</sup>	land capability and planning/identifying areas of major soil limitations	0.5–1.0 per km <sup>2</sup>	0.1–0.2 per km <sup>2</sup>	0.2–1.0 per 25 km <sup>2</sup>
1:50 000	25 ha	land capability and planning/identifying areas of major soil limitations	2–4 per km <sup>2</sup>	0.5–1.0 per km <sup>2</sup>	0.04–0.20 per km <sup>2</sup>
1:25 000	6.25 ha	agriculture/broad scale planning	6–18 per km <sup>2</sup>	1.5–3.0 per km <sup>2</sup>	0.1–0.5 per km <sup>2</sup>
1:10 000	1.0 ha	intensive agriculture/low intensity urban	0.5–1.0 per km <sup>2</sup>	10–20 per km <sup>2</sup>	0.5–4.0 per km <sup>2</sup>
1:5000	0.25 ha	intensive agriculture/moderately intensive urban	2–4 per ha	0.5–1.0 per ha	0.04–0.20 per ha
1:1000	100 m <sup>2</sup>	intensive agriculture and urban development	50–100 per ha	10–20 per ha	0.5–4 per ha

**Table 1.3.** Soil survey effort as minimum number of days in the field for different scales

Scale	Days in the field per km <sup>2</sup>	Days required for a 100 km × 100 km area	km <sup>2</sup> per day in the field
1:5000	40.078	400 000	0.025
1:10 000	13.496	135 500	0.075
1:15 000	7.140	71 400	0.140
1:20 000	4.545	45 500	0.220
1:25 000	3.201	32 000	0.312
1:30 000	2.404	24 000	0.416
1:50 000	1.078	10 800	0.928
1:100 000	0.363	3600	2.755
1:250 000	0.086	860	11.613
1:500 000	0.029	300	34.487
1:1 000 000	0.010	100	102.415

# 2

## Soil physical properties

Soil physical fertility or soil structure can have as large an impact on plant growth as chemical fertility. Several suggested critical values for soil physical properties are presented in this section, but further discussion of soil physical fertility and soil structure is presented in Cass (1999) and Geeves *et al.* (2007a).

### 2.1 Particle size distribution

#### 2.1.1 The relationship between field texture and particle size

Particle size distribution describes the relative amounts of gravel, sand, silt and clay within the soil. These are the building blocks for the soil and can have a large effect on the soil properties (see Table 2.1). Clays have a high surface area of 5–750 m<sup>2</sup>/g depending on clay type and can have a high amount of chemical and physical activity. Sands have a smaller surface area (0.100–0.01 m<sup>2</sup>/g) and tend to be less chemically and physically active (McKenzie *et al.* 2004).

Table 2.1. Particle size

Particle description	Size (mm)	Size (μm)	Likely surface area m <sup>2</sup> /g (McKenzie <i>et al.</i> 2004)
Clay	<0.002	2	5–750
Silt	0.002–0.02	2–20	1.0
Fine sand	0.02–0.2	20–200	0.1
Coarse sand	0.2–2	200–2000	0.01
Fine gravel	2–6	2000–6000	<0.01
Coarse gravel	>6	>6000	<<0.01

This particle size scale is equivalent to the International Scale for particle size description.

Note that in the US system, silt is defined as 0.02–0.05 mm and fine sand as 0.05–0.20 mm.

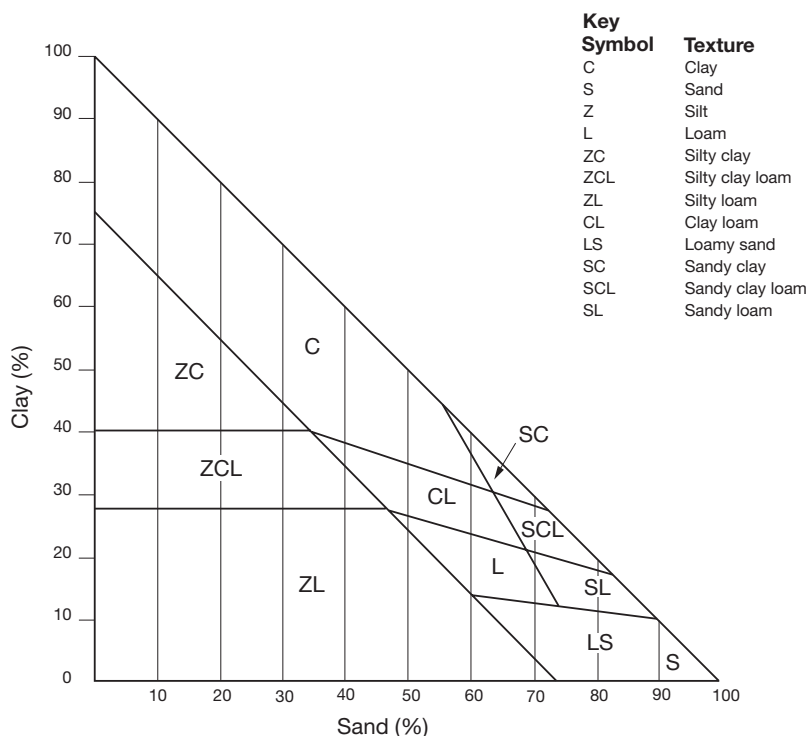
Table 2.2 is a guide to the description used for the proportion of each type of particle in soil.

**Table 2.2.** General levels of different particle size contained in a soil

Percentage of particle (e.g. clay, sand or silt)	Description of the relative amount of a size fraction or particle in soil
<10	very low
10–25	low
25–40	moderate
40–50	high
>50	very high

Examples: <10% clay = very low level of clay; >50% silt = very high level of silt.

There is also an approximate relationship between field texture and particle size distribution, as shown in Figure 2.1. (See McDonald *et al.* (1994) for method for field texturing.)



**Fig. 2.1.** Soil texture triangle (adapted from Soil Science, University of Sydney, 1991). This triangle is effectively equivalent to that in McDonald *et al.* (1994) but is easier to use because there are only two variables. This simplification is possible because clay + silt + sand always add up to 100%. Example: 20% clay and 67% sand will give a loam texture.

To estimate field texture grade from laboratory measurements:

**Step 1.** Add fine and coarse sand fraction.

**Step 2.** Construct a line at right angles to % sand line (% sand).

**Step 3.** Construct a line at right angles to % clay line (% clay).

**Step 4.** The point where the lines intersect gives the approximate texture group.

## 2.1.2 Field texture and estimated clay content

There are several interpretations for the comparison of field texture and estimated clay content (see Tables 2.3–2.4).

**Table 2.3.** The Northcote interpretation

Texture group	Texture grade	Estimated clay content (%)
1. Sands	sand	<10 and commonly <5
	loamy sand	5–10
	clayey sand	5–10
2. Sandy loams	sandy loam	10–15
	fine sandy loam	10–20
	light sandy clay loam	15–20
3. Loams	loam	about 25
	loam, fine sandy	about 25
	silt loam	about 25, with >25% silt
	sandy clay loam	20–30
4. Clay loams	clay loam	30–35
	silty clay loam	30–35, with >25% silt
	fine sandy clay loam	30–35
5. Light clays	sandy clay	35–40
	silty clay	35–40, with >25% silt
	light clay	35–40
	light medium clay	40–45
6. Medium–heavy clays	medium clay	45–55
	heavy clay	>50

Source: Northcote (1979).

**Table 2.4.** The interpretation of McDonald *et al.* (1994)

Texture grade	Estimated clay content (%)
Sand	commonly <5
Loamy sand	about 5
Clayey sand	5–10
Sandy loam	10–20
Loam	about 25
Silty loam	about 25, with silt >25%
Sandy clay loam	20–30
Clay loam	30–35
Clay loam, sandy	30–35
Silty clay loam	30–35%, with silt >25%
Light clay	35–40
Light medium clay	40–45
Medium clay	45–55
Medium–heavy clay	>50
Heavy clay	>50

Source: McDonald *et al.* (1994).



Where sand is recorded in a texture the dominant sand size is defined as ‘fine’ when it is in the size range 0.02–0.20 mm, or ‘coarse’ when it is in the size range 0.2–2.0 mm. Coarse sand grains are visible with the naked eye in the soil sample. Fine sand is not visible with the naked eye and its presence is detected by feel and a grinding sound during hand-texturing.

### 2.1.3 Particle sizes for the Unified Soil Classification System

Note that there are variations in particle size categories for the Unified Soil Classification System (USCS), which is used for engineering (Hicks 2007).

The USCS sizes are:

fines (silts and clays)	<0.074 mm
fine sand	0.074–0.420 mm
medium sand	0.42–2.00 mm
coarse sand	2.00–4.76 mm
fine gravel	4.76–20.00 mm
coarse gravel	20–75 mm

### 2.1.4 Key references

Northcote (1979); McDonald *et al.* (1994); Cass (1999); Geeves *et al.* (2007a); Hicks (2007).

## 2.2 Water-holding properties

### 2.2.1 Definitions and units

#### Moisture content

##### a. Gravimetric

Moisture is expressed as weight of water per weight of oven dry soil, usually as g/g ( $\theta_g$ ) or as g water per 100 g of oven dry soil (%).

##### b. Volumetric

Moisture is expressed as the volume of water per volume of soil, usually as  $\text{cm}^3/\text{cm}^3$  ( $\theta_v$ ). This converts to depth of water per depth of soil for a unit area. It can be expressed as centimetre of water per centimetre of soil, or, more conveniently, millimetres of water per centimetre of soil, or millimetres of water per metre of soil.

Volumetric moisture is derived from gravimetric moisture by using bulk density and the density of water in the following equation:

$$\text{Volumetric moisture} = \text{gravimetric moisture} \times \frac{\text{bulk density}}{\text{density of water}}$$

Volumetric moisture can be measured directly using neutron probes (Gardner 1986) and Time Domain Reflectometry (TDR) (Ansault *et al.* 1984; Zegelin *et al.* 1990).

##### c. Moisture potential

Water is held in soil under a negative pressure and energy has to be applied to remove the water from the soil. The amount of energy required is termed the moisture potential. In

general, the Field Capacity of the soil is the amount of water held in a soil when it has been allowed to drain (usually for 48 hours) and corresponds to  $-10$  to  $-30$  kPa of pressure. At Permanent Wilting Point, the water in the soil is held at negative pressures sufficiently high that plants can no longer extract the water. This is generally considered to be at  $-1500$  kPa.

The available water for plant growth is the amount of water held in the soil between the Field Capacity and Permanent Wilting Point. See Cass (1999), Geeves *et al.* (2007a) and McKenzie *et al.* (2004) for further detail on the scientific basis for these soil properties.

Note that some managers for irrigated crops and trees use the 'Readily Available Water-holding Capacity', which is the water held between  $-8$  and  $-60$  kPa.

## 2.2.2 Typical values of water-holding capacity

The moisture characteristic of a soil defines the amount of water held in a soil at each moisture potential. An approximation of the moisture characteristic can be made from soil texture and structure.

Using the model of the moisture characteristic:

$$\ln(\psi) = a + b \ln(\theta)$$

where  $\psi$  is the moisture potential and  $\theta$  is the moisture content.

Williams *et al.* (1983) determined the moisture characteristic for a group of 78 soils. They grouped the soils into eight classes with the moisture holding properties shown in Table 2.5. These are only estimated values and caution is required in their application. For specific sites, moisture contents at  $-10$  kPa and  $-1500$  kPa should be determined by methods described in Burke *et al.* (1986); Geeves *et al.* (1995); Geeves *et al.* (2007a) and McKenzie *et al.* (2002).

The water-holding capacity of the soil is dependent on a range of soil properties. These include:

- particle size distribution, with coarse sands holding the least water and clays the most, but silts and fine sands holding the most water in the available water range
- the type of clay, with montmorillonite or swelling clays holding more water than kaolin-type clays
- the amount of organic matter in the soil
- the bulk density and structure of the soil.

Various schemes to predict water-holding capacities from readily available soil properties such as texture and structure are available and frequently used, and are generally termed pedotransfer functions (McBratney *et al.* 2002). A selection of these is presented in Tables 2.5–2.6, but this is not a complete list.

**Table 2.5.** Water-holding capacities for soil types, based on Williams *et al.* (1983)  
MTG, mean texture group based on Northcote (1979) (see Table 2.3). Moisture contents are volumetric moisture contents.

Group	Characteristics	Field capacity: volumetric moisture % 10 kPa	Permanent wilting point: volumetric moisture % 1500 kPa	Available water		
				(%) by volume	(mm/m)	(mm/cm)
1	apedal loamy sands to coarse sandy loams (5.2% clay, MTG 1.2)	20	4	16	160	1.6
2	weakly pedal fine sandy loams with some silt (21.7% clay, MTG 2.5)	30	10	20	200	2.0
3	weakly pedal sandy clay loams to coarse sand (24.1% clay, MTG 4)	29	17	12	120	1.2
4	clay loams to light clay fine sand and silt (38.7% clay, MTG 4.7)	40	16	24	240	2.4
5	loam to clay loam high silt and organic matter fine structure (28.7% clay, MTG 3.3)	48	20	28	280	2.8
6	coarse structured light to medium clay (44% clay, MTG 5.3)	38	25	13	130	1.3
7	moderate sized structure medium clay (50% clay, MTG 5.9)	41	29	12	120	1.2
8	structured medium clay to heavy clay (55% clay, MTG 5.9)	47	34	13	130	1.3

Adapted from Williams *et al.* (1983).

**Table 2.6.** Estimating available water-holding capacity (AWC) from soil texture, sand size and soil structure  
(from Moore *et al.* 1998)

Texture	% clay	Sand size fraction	AWC (mm water/m soil)	
			Moderate to strong structure	Weakly structured to apedal
Sand	<5%	coarse to very coarse	—	~20
		medium to coarse	—	30–45
		medium	—	40–50
		fine	—	50–70
Loamy sand/clayey sand	5–10%	coarse	—	50–60
		medium	—	60–90
		fine	—	80–100
Sandy loam	15–20%	coarse	110–220	50–60
		medium	110–170	60–100
		fine	170–220	~140
Light sandy clay loam	15–20%	coarse	120–150	50–60
		medium	170–220	90–100
		fine	~180	100–120
Loam	~25%	—	150–240	100–130
Sandy clay loam	20–30%	—	130–190	100–130
Clay loam	30–35%	—	120–210	~100
Sandy clay	35–40%	—	130–150	80–100
Clay	>35%	—	110–120	90–140
Clay (self-mulching)	>35%	—	~210	—

Care should be taken in applying these values in the development of specific water management plans. Often local information is used to predict water-holding values for specific water management plans.

The available soil water-holding capacity (ASWC) is the amount of water held in the entire soil profile between field capacity (FC) and permanent wilting point (PWP) (see Tables 2.7–2.8).

**Table 2.7.** Available soil water-holding capacity (ASWC) for a soil profile

ASWC (mm water per m soil)	Rating
<100	low
100–200	medium
>200	high

Source: McIntyre (1974).

**Table 2.8.** Pressure units commonly used to measure moisture potential and their approximate conversions

\*, joules per kilogram; \*\*, field capacity natural field condition; \*\*\*, field capacity sieved and ground soil.

Moisture potential – pressure						
	cm water	kPa	Atmosphere or bars	MPa	J/kg*	lb/in <sup>2</sup>
FC1**	1	0.1	0.001	0.0001	0.1	0.015
	4	0.4	0.004	0.0004	0.4	0.058
	100	10	0.1	0.01	10	1.45
FC2***	300	30	0.33	0.03	30	4.35
	1000	100	1.0	0.10	100	14.6
Permanent wilting point	15 000	1500	15	1.50	1500	218

### 2.2.3 Moisture balance calculations

Moisture balance calculations can predict the amount of water in the soil and the rate at which plants transpire the water in the soil, passing it back into the atmosphere.

Moisture balance can be calculated using methods described in:

- Cresswell *et al.* (1992) and with the SWIM program developed by CSIRO (Ross 1990)
- PERFECT program developed by Queensland DPI (Littleboy *et al.* 1989) and TOPOG (Dawes and Hatton 1993).
- CLASS program developed by the NSW Department of Natural Resources (Tuteja *et al.* 2004) and <http://www.toolkit.net.au/cgi-bin/WebObjects/toolkit.woa>

In moisture balance calculations the demand for water in the soil is related to the daily evaporation rate. The amount of water that plants transpire and the amount of water that evaporates from the soil is driven by the potential evaporation rate. The potential evaporation rates given in Table 2.9 are based on an open-water surface and actual evaporation rates will be less than this if there is insufficient water in the soil. The rates give an indication of demand by plants for water at different times of the year.

**Table 2.9.** Daily evaporation rates

Zone	Location	Average daily evaporation (mm/d)			
		Jan.	Mar.	July	Oct.
Arid	Broken Hill	9.8	6.7	2.0	6.2
North-west slopes	Gunnedah	6.3	4.7	1.3	3.9
Northern tablelands	Tenterfield	5.6	3.7	1.2	3.7
North coast	Kempsey	4.1	3.3	1.2	3.3
Central west slopes	Forbes	8.2	4.9	1.3	4.1
Central tablelands	Orange	7.0	4.4	1.2	3.7
Hunter Valley	Cessnock	5.2	3.6	1.4	3.3
South-west slopes	Junee	7.0	4.4	1.1	3.4
Southern tablelands	Braidwood	5.7	3.3	1.1	2.8
South coast	Narooma	4.1	3.3	1.2	2.7
Riverina	Deniliquin	8.2	4.9	1.2	2.9
Snowy Mtns	Spencers Ck	3.7	2.5	1.0	2.1

Source: Edwards (1979).

## 2.2.4 Key references

Williams *et al.* (1983); Cresswell *et al.* (1992); Geeves *et al.* (2007a); McKenzie *et al.* (2002).

## 2.3 Hydraulic conductivity (K)

### 2.3.1 Definition and units

Hydraulic conductivity is the flow of water through soil per unit of energy gradient. For practical purposes, it is a measure of the rate at which water moves into and through the soil. It is useful for predicting runoff from rainfall, soil drainage, irrigation rates, leaking from dams and deep drainage that contributes to salinity (Cass 1999). Dimensions are depth per unit time and typical units are mm/d and others shown in Table 2.10.

**Table 2.10.** Units and their conversions commonly used in calculating hydraulic conductivity

m/s	mm/h	mm/d	cm/d	cm/yr
1	$3.60 \times 10^6$	$8.64 \times 10^7$	$8.64 \times 10^6$	$3.154 \times 10^9$
$2.78 \times 10^{-7}$	1	24	2.4	876
$1.16 \times 10^{-8}$	0.042	1	0.1	36.5
$1.16 \times 10^{-7}$	0.42	10	1	365
$3.17 \times 10^{-10}$	$1.14 \times 10^{-3}$	$2.74 \times 10^{-2}$	$2.74 \times 10^{-3}$	1

### 2.3.2 Methods of measurement

Hydraulic conductivity (K) can be measured by several methods. Two basic methods are:

- Ponded or positive head that measures saturated hydraulic conductivity using rings or cores ( $K_{\text{sat}}$ ), when a constant rate has been reached (Klute and Dirksen 1986; McKenzie and Cresswell 2002).

**Table 2.11.** A comparison of the pore sizes contributing to water flow under the different methods

Method of measuring K	Diameter of the largest pore size contributing to the water flow (mm)
Ponded ( $K_{\text{sat}}$ )	All pores regardless of size
Suction (–10 mm)( $K_{10}$ )	3.0
Suction (–40 mm)( $K_{40}$ )	0.75

- Unsaturated or negative head: most commonly measured with disc permeameters. In this case the hydraulic conductivity is measured under suction and the soil has to draw the water out of the disc permeameter. The size of pores contributing to water flow is determined by the suction applied (see Table 2.11). (Perroux and White 1988; Coughlan *et al.* 1991; Cook and Broeren 1994; Cass 1999 and McKenzie *et al.* 2002.)

The most appropriate measure of hydraulic conductivity depends on the purpose for which the measurements are made and the nature and macroporosity of the soil for which the values are determined.

In many cases  $K_{10} \approx K_{\text{sat}}$ , depending on the presence of pores greater than 3.0 mm. A discussion on how the relative sizes change with cropping practices is presented in Murphy *et al.* (1993).

### 2.3.3 Typical values of hydraulic conductivity

**Table 2.12.** Typical values of saturated hydraulic conductivity based on texture and degree of structure

\*, strongly structured polyhedral subsoils e.g. Krasnozern or Dermosol.

(The values shown are estimates only, and should be used with caution.)

Texture	Structure	Infiltration	Permeability (mm/h.)
Sand	apedal	very rapid	>120 can be as high as >250
Sandy loam	weakly pedal	very rapid	>120
	apedal	rapid	60–120
Loam	peds evident	rapid	60–120
	weakly pedal	moderately rapid	20–60
	apedal	moderately rapid	20–60
Clay loam	peds evident	moderately rapid	20–70
	weakly pedal	moderate	5–20
	apedal	slow	2.5–5
Light clay	highly pedal	moderate	5–50*
	peds evident	slow	2.5–10
	weakly pedal	very slow	<2.5
Medium to heavy clay	highly pedal	low to moderate	2.5–50*
	peds evident	very slow	<5.0
	weakly pedal	very slow	<2.5
Clay	sodic and saline	moderate	8.0
	sodic	very slow	<2.5
	highly sodic	extremely slow	<1.0

Adapted from Geeves *et al.* (2007a).

### 2.3.4 Suggested interpretation of saturated hydraulic conductivity rating and its implication for management

**Table 2.13.** Indicative values of saturated hydraulic conductivity rating

Saturated hydraulic conductivity (mm/h.)	Rating	Interpretation
<0.5	extremely low	Suitable for water storage (1).
0.5–10	very low	Likely to cause regular runoff under rainfall; irrigation likely to be inefficient (2).
10–20	low	Runoff less regular (3) and soil is becoming suitable for irrigation (4).
20–60	moderate	Runoff only occasional and soil is suitable for irrigation.
60–120	high	Runoff rarely occurs and soil is becoming too permeable for irrigation (5).
>120	very high	If soil is used for effluent or waste disposal there may be potential problems with contamination of water tables (6).

These interpretations are based on the authors' experience and discussions with field staff. They are intended only as a general guide, and should be used with caution. They are based on the following indicators:

(1) A water store of 5 m depth should hold water for at least one year. Soils are unsuitable for disposal of wastewater or effluent. (2) The majority of rain falls at intensities of less than 10 mm/h. (3) When soil is saturated, runoff will occur even with low intensity rainfall. (4) Irrigation is difficult for soil with  $K_{\text{sat}} < 10$  mm/h. because: high runoff rates necessitate low application rates ( $< 10$  mm/h.); the length of time sprays need to be kept operating becomes costly; and it is difficult to replenish soil water when evaporation rates are high. (5) Flood and sprinkler irrigation become very costly and difficult if soil permeabilities are too high. (6) Soils with very high hydraulic conductivity are not suitable for effluent or wastewater disposal as the wastewater passes through the soil so rapidly that it remains untreated, or unaltered.

Note: The return period for storms of various intensities and durations is presented in Pilgram (1987). Prediction of runoff is based on the soil being unsaturated so that water is still able to infiltrate into the soil. When the soil is saturated, runoff will occur even at low rainfall intensities.

**Table 2.14.** Interpretation of saturated hydraulic conductivity rating by Hunt and Gilkes

Drainage class	What this means on your farm or garden	Hydraulic conductivity (cm/min.)	Hydraulic conductivity (mm/d.)	Hydraulic conductivity (mm/h.)	Descriptive term for rainfall
Extremely slow to very slow	Liable to waterlog; land restricted to shallow-rooted plants.	$< 0.0006$ to $0.0006\text{--}0.0020$	$< 8.5$ to $8.5\text{--}30.0$	$< 0.35$ to $0.35\text{--}1.25$	fine mist to drizzle
Slow to moderately slow	Poor infiltration may lead to overland flow and erosion on slopes.	$0.002\text{--}0.008$ to $0.008\text{--}0.030$	$30\text{--}120$ to $120\text{--}480$	$1.25\text{--}5.00$ to $5.00\text{--}20.00$	slight to moderate rainfall
Moderate to moderately rapid	No problems except on very steep slopes where erosion could occur.	$0.03\text{--}0.14$ to $0.104\text{--}0.208$	$480\text{--}1500$ to $1500\text{--}3000$	$20\text{--}62$ to $62\text{--}125$	downpour to violent rainfall
Rapid to very rapid	No problems except on very steep slopes where erosion could occur.	$0.208\text{--}0.417$ to $> 0.417$	$3000\text{--}6000$ to $> 6000$	$125\text{--}250$ to $> 250$	violent to very violent rainfall

Source: Klute (1965); Hunt and Gilkes (1992).

### 2.3.5 Unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity of the soil can be measured by applying water that is under tension to the soil. This can be done using instruments such as a disc permeameter (Perroux and White 1988; McKenzie *et al.* 2002). These measures of unsaturated conductivity are at the wet end of the moisture characteristic and cannot be used to predict most of the unsaturated flow in soils. Unsaturated flow can often be predicted by using the moisture characteristic (van Genuchten *et al.* 1989).

The interpretation of results for disc permeameters is dependent on the tension at which the measurements are made.

(i) 10 mm tension ( $K_{10}$ )

Generally the ratings in Section 2.3.4 (suggested interpretation of saturated hydraulic conductivity rating and its implication for management) for  $K_{\text{sat}}$  may be used.

(ii) 40 mm tension ( $K_{40}$ )

These tend to be relatively uniform and are commonly less than 10 mm/h. In many cases  $K_{40}$  may be considered an estimate of the hydraulic conductivity when a soil is structurally degraded, or as a rate at which water may be added to the soil and still maintain a high level of aeration as may be required in some effluent disposal systems (see Murphy *et al.* 1993).



### 2.3.6 Hydraulic conductivities of common regolith and rock materials

**Table 2.15.** Typical porosities and hydraulic conductivities for common regolith and rock materials based on data in Taylor and Eggleton (2001: 82) using data from Morris and Johnson (1967) and Thomas (1994)  
nd, no data.

Materials	Porosity (%)	Saturated hydraulic conductivity (mm/h.)	Saturated hydraulic conductivity (mm/d.)
<b>Regolith materials</b>			
Gravel	25	>36 000	864 000
Sand	35	0.126–720	3.0–17 300
Coarse sand	nd	0.126–9000	3.0–216 000
Fine sand	nd	0.36–250.00	8.6–6050
Silty sand	nd	3.6	86
Sandy clay	nd	1.8	40
Silt	34–61	0.0036–9.4	0.086–225
Silty clay	nd	0.036	0.86
Clay	34–57	<0.0036	0.086
Aeolian sand	40–51	14–936	340–22 500
Till	nd	0.0036–1660	0.0864–39 700
Granite – weathered	34–57	3.6–72	86.4–1728
Gabbro – weathered	41–45	0.65–5	15.6–120
<b>Rock materials</b>			
Granite	0.5–1.5	nd	nd
Basalt	0.1–1.0	nd	nd
Basalt	3–35	0–0.60	0–14
Schist	4–49	0–15	0–360
Slate	0.1–0.5	0–0.0036	0–0.086
Marble	0.5–2.0	nd	nd
Limestone	7–56	0–340	0–8200
Sandstone	2–25	nd	nd
Sandstone – fine grained	2–40	0–30	0–730
Sandstone – medium grained	12–41	0.03–140	0.69–3370
Shale	10–30	nd	nd
Shale	1.4–9.7	<0.036	<0.86

(Deeper and buried regolith and rock materials that are often compacted and not as well structured as surface soil materials are likely to have much lower hydraulic conductivities than surface soils. Values can also be higher for fractured rock.)

### 2.3.7 Key references

Klute (1965); Klute and Dirksen (1986); Pilgram (1987); Perroux and White (1988); Hunt and Gilkes (1992); Cook and Broeren (1994); Cass (1999); Geeves *et al.* (2007a); Taylor and Eggleton (2001); McKenzie *et al.* (2002).

## 2.4 Bulk density and air porosity

### 2.4.1 Bulk density

Bulk density ( $\rho_b$ ) is the oven dry weight of soil per unit volume. It may be expressed in  $\text{g/cm}^3$  or  $\text{t/m}^3$  ( $1 \text{ g/cm}^3 = 1000 \text{ kg/m}^3 = 1 \text{ t/m}^3$ ). It affects porosity and soil strength. Bulk density is a measure of the density of a porous material that takes into account the density of the solid material ( $\rho_s$ ) and the amount of porosity ( $f$ ).

A full description of bulk density and porosity is presented in Cresswell and Hamilton (2002).

### 2.4.2 Total porosity and typical values of bulk density

Total porosity ( $f$ ) is the proportion of the soil volume occupied by pores (including air and water). It can be calculated from the following:

$$f = 1 - \frac{\rho_b}{\rho_s}$$

where  $\rho_s$  is the average specific gravity of soil particles, taken to be  $2.65 \text{ g/cm}^3$  in many cases.

Typical bulk densities of soil materials and densities of rock and various minerals are shown in Tables 2.16 and 2.17.

**Table 2.16.** Typical values of density and porosity of soil materials and densities of rock materials

nd, no data.

	Density (g/cm <sup>3</sup> )	Porosity (%)
<b>General bulk densities for soils</b>		
Rock (assuming all quartz)	2.65	0
Sodic clay	2.0	25
Dense pan	1.8	32
Wall of a farm dam	1.7	36
Agricultural soil	1.4	47
<b>Densities of important rock types and minerals (Encyclopaedia Britannica 1991). (Weathered materials from these rocks will have lower bulk densities.)</b>		
Feldspar	2.56	nd
Quartz	2.65	nd
Pyroxene	3.40	nd
Olivine	3.50	nd
Granite	2.5–2.8	0.3–1.5
Diorite	2.7–3.0	0.5
Gabbro	2.9–3.1	0.5
Peridotite (ultrabasic)	3.1–3.3	0.5
Eclogite (ultrabasic)	3.3–3.6	0.5
Gneiss	2.6–3.1	0.5
Schist	2.7–3.0	0.5
Slate	2.70–2.85	4.0
Quartzite	2.64	0.5
Basalt (crystalline)	2.2–3.0	1–30
Basalt (glass)	2.70–2.85	low
Pumice	0.5–1.0	60–90
Sandstone (young)	1.9–2.2	10–35
Sandstone (older and compacted)	2.3–2.5	5–25
Shale (young)	1.8–2.2	15–35
Shale (older and compacted, deep)	2.6–2.7	4–7
Limestone	2.5–2.7	0.1–15

**Table 2.17.** A list of densities of common minerals presented in Cresswell and Hamilton (2002: 52)

Mineral	Density (g/cm <sup>3</sup> )
Albite	2.62
Anatase	3.90
Anorthite	2.76
Apatite	3.15–3.20
Aragonite	2.95
Bauxite	2.00–2.55
Beidellite	2.00–3.00
Biotite	2.80–3.20
Calcite	2.71
Chert	2.65
Chlorite	2.60–3.30
Dolomite	2.85
Epidote	3.35–3.45
Gibbsite	2.30–2.40
Goethite	4.37
Gypsum	2.32
Halite	2.16
Halloysite	2.00–2.20
Hematite	5.26
Hornblende	3.00–3.40
Ilmenite	4.70
Jarosite	~3.20
Kaolinite	2.60
Lepidocrite	4.09
Ferrihydrite	3.60–4.00
Magnetite	5.18
Montmorillonite	2.50
Muscovite	2.50
Oligoclase	2.65
Olivine	3.27–4.37
Opal	2.00–2.25
Orthoclase	2.57
Plagioclase	2.62–2.76
Pyrite	5.02
Quartz	2.65
Rutile	4.18–4.25
Talc	2.70–2.80

### 2.4.3 Limiting values of bulk density

Limiting values of bulk density for plant growth depend on soil texture (Cass 1999).

In Tables 2.18, 2.19 and 2.20, the critical values of bulk density for plant growth at which root penetration is likely to be severely restricted are shown. These are a guide only. Roots may penetrate through existing pores or planes of weakness in the soil, such as cracks between soil structural units, and this is not taken into account in these values.

**Table 2.18.** Critical values of bulk density for plant growth at which root penetration is likely to be severely restricted

Texture	Critical bulk density (g/cm <sup>3</sup> )
Sandy loam	1.8
Fine sandy loam	1.7
Loam and clay loam	1.6
Clay	1.4

Source: Jones (1983).

**Table 2.19.** Effect of bulk density on soil condition

Bulk density (g/cm <sup>3</sup> )	Sandy soils	Loams	Clay soils
<1.0	–	satisfactory	satisfactory
1.0–1.2	–	satisfactory	satisfactory
1.2–1.4	very open	satisfactory	some too compact
1.4–1.6	satisfactory	some too compact	very compact
1.6–1.8	mostly too compact	very compact	highly compact
>1.8	very compact	extremely compact	excessively compact

Source: Handreck and Black (1984); Hunt and Gilkes (1992).

**Table 2.20.** A general scale of bulk density

Bulk density (g/cm <sup>3</sup> )	Rating
<1.0	very low
1.0–1.3	low
1.3–1.6	moderate
1.6–1.9	high
>1.9	very high

Source: Harte (pers. comm.).

### 2.4.4 Air porosity

Air porosity (or volumetric air content) is the proportion of soil volume occupied by air, and this varies with moisture content. Most plants cease to grow when air porosity falls below 10%. Within the soil there may be pockets of air, such as cracks between peds or large biopores, where there is sufficient aeration for plant growth. The amount of air porosity in the soil is a useful guide to the conditions for plant growth and biological activity and relates to the conditions in the majority of the soil (Murphy 2000). Air porosity can be calculated from the following equation:

$$f_{\text{air}} = f - \theta_v$$

Air porosity (%) = total porosity (%) – volumetric moisture content (%)

As a general rule, air porosity at field capacity should be greater than 10% for adequate aeration, for plant growth and for biological activity. However, some plants such as rice or reeds can grow with much lower levels of aeration.

An indication of the relationship between air porosity, gravimetric moisture content and bulk density can be obtained from Fig. 2.2 (assuming density of soil solids is  $2.65 \text{ g/cm}^3$ ). Bulk density has a strong effect on air porosity at field capacity. A useful discussion of the balance between air porosity at field capacity and available water is presented in Cass (1999: fig. 6.2). This shows that soils occur with various combinations of air porosity at field capacity and total available water. The better structured soils have a combination of high total available water and air porosity at field capacity, and the more limiting soils have a combination of low air porosity at field capacity and low total available water.

In clays with higher gravimetric moisture contents at field capacity, air porosity becomes limiting at a lower bulk density than it does in less clayey soil, which has a lower moisture content at field capacity (see Tables 2.21–2.22).

**Table 2.21.** Bulk density required to give 10% air porosity at different gravimetric moisture contents (Assuming soil solid density =  $2.65 \text{ g/cm}^3$ .)

Gravimetric moisture content (%)	Bulk density to give 10% air porosity ( $\text{g/cm}^3$ )
5%	2.10
10%	1.90
20%	1.55
30%	1.33
40%	1.15

**Table 2.22.** Generalised view of pore size groups and functions

\*, equivalent particle size =  $3.2 \times$  pore size (assuming spherical, uniform size particles); \*\*, based on the equation: pore diameter (mm) =  $0.30/\text{soil water tension (kPa)}$  (Marshall and Holmes 1979).

Pore size (mm)	Function	Equivalent particle* or aggregate size (mm)	Equivalent** soil water tension (kPa)
>0.50	aeration and water transmission	>1.6 (mostly gravel size, some coarse sand size)	<0.6
0.50–0.05	water transmission (infiltration, permeability)	0.16–1.60 (mostly coarse sand size, some fine sand size)	0.6–6.0
0.05–0.0005	storage (water-holding capacity, plant available water)	0.0016–0.16 (mostly silt and fine sand size, some clay size)	6.0–600
<0.0005	residual (very strongly bound water, unavailable to plants)	<0.0016 (mostly clay size)	>600

Source: Greenland (1981); Geeves *et al.* (2007a).

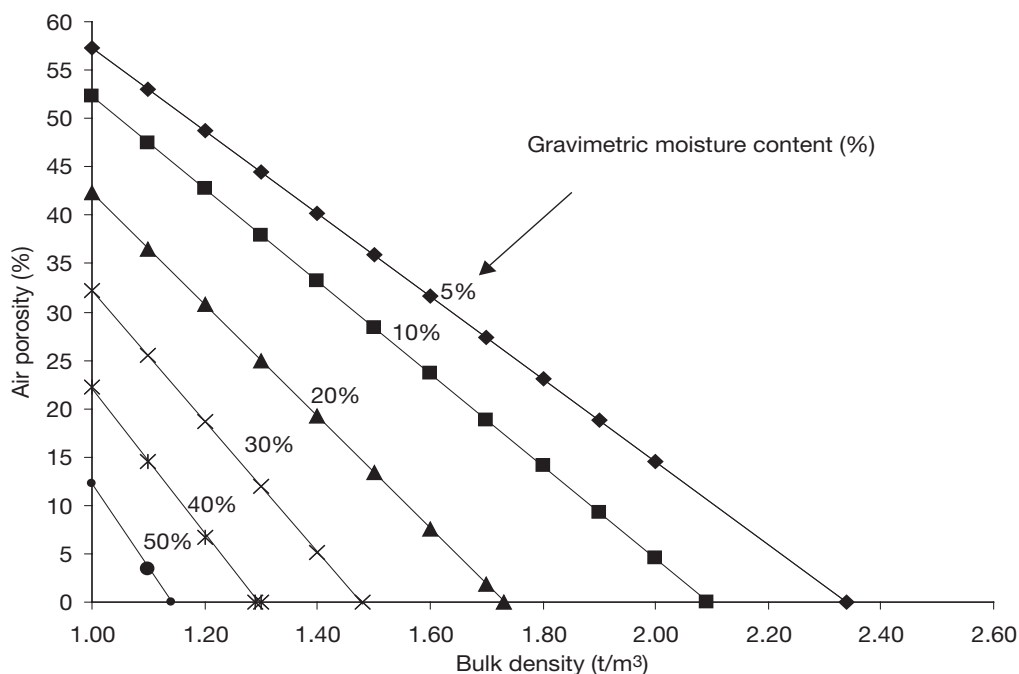


Fig. 2.2. Air porosity, bulk density and moisture content.

### 2.4.5 Converting bulk density to soil mass

For many chemical tests on soils, the results from the laboratory are presented as a chemical concentration expressed as the amount of the element or compound per unit weight of soil. This may be expressed as a weight per gram of soil (e.g. %, ppm, mg/kg) or a molarity-based unit (centimole of positive charge) per unit of soil. However, for many applications it becomes necessary to convert this concentration based on soil mass into a concentration based on soil volume ( $\text{m}^3$ ) or area ( $\text{ha}$  or  $\text{m}^2$ ).

The mass of soil in a specified area is given by:

$$\text{mass of soil} = \text{area} \times \text{depth} \times \text{bulk density}$$

or

$$\text{mass of soil (tonnes per hectare)} = \text{area (100} \times 100 \text{ m}^2 \text{ per hectare)} \times \text{soil depth (m)} \times \text{bulk density (t/m}^3\text{)}$$

(Note that a depth of soil must be specified to obtain a value.)

Once the mass of soil per unit area to the specified depth is known or estimated, the amount of the element or compound per unit area is calculated as:

Amount of element or compound per hectare to the specified depth =  
measured gravimetric concentration per mass of soil  $\times$  specified mass of soil per hectare.

### 2.4.6 Key references

Marshall and Holmes (1979); Greenland (1981); Jones (1983); Handreck and Black (1984); Hunt and Gilkes (1992); Cass (1999); Cresswell and Hamilton (2002); Geeves *et al.* (2007a).

## 2.4.7 Further reading

Cass (1999).

# 2.5 Soil strength

## 2.5.1 Soil strength

Soil strength determines the resistance of soil to failure or shearing. In order to grow, plant roots often need to shear the soil. The value of soil strength that limits root growth depends upon how the soil strength is measured. The soil strength is very dependent on the moisture content at which it is measured and this needs to be taken into account when interpreting results. The units used for soil strength are commonly kiloPascals (kPa), or in the case of high soil strength, megaPascals (MPa).

## 2.5.2 Limiting values for penetrometer resistance using a cone penetrometer

Penetrometer resistance is commonly used as an indicator of soil strength and is frequently measured with a standard cone. The standard cone has a 30° angle and a base of 12.82 mm. It conforms to ASAE Standard S313.1 (ASAE 1983) and is similar to that described by Anderson *et al.* (1980). The resistance is commonly recorded initially at 5 mm and then at 15 mm intervals to 440 mm as the penetrometer is pushed into the soil at a rate of 30.5 mm/s. The data is recorded on an electronic data logger.

Root growth may not always directly reflect these limitations because roots can still grow into cracks, fissures and old biopores, which may not be detected by the penetrometer. However, once a penetrometer resistance of 2.4 MPa is reached, root growth is largely restricted to existing pores or planes of weakness. This greatly limits the volume of soil that may be accessed by the roots, particularly in a soil with few existing cracks or pores (see Table 2.23).

**Table 2.23.** Effect of penetration resistance on root growth

\*, the resistance is very dependent on moisture content and technique.

Penetration resistance* (MPa)	Degree of soil consolidation	Effect on root growth
<0.50	loose	not affected
0.50–1.25	medium	root growth of some cereal plants may be restricted
1.25–2.00	dense	cereal root growth badly restricted
2.00–3.00	very dense	very few plant roots penetrate the soil
>3.00	extremely dense	root growth virtually ceases

Adapted from Marshall and Holmes (1979); Ball and Sullivan (1982); Passioura (1991); Hunt and Gilkes (1992) and Cass (1999).



### 2.5.3 The balance between soil strength and available air – the non-limiting water range

The limitations to root growth are a balance between a suitable air porosity and low soil strength. As the soil becomes drier the air porosity increases, but the soil strength increases and becomes more limiting. As the soil becomes wetter the reverse conditions occur. The soil moisture range where there is sufficient air for root growth and the soil strength is low enough for root growth is termed the non-limiting water range (NLWR) (Letey 1985, 1991). Well-structured soils in good physical condition have a wide range of moisture contents in the NLWR. Poorly structured soils have a narrow NLWR and some soils such as the worst affected sodic subsoils have no NLWR and root growth is severely limited at all moisture contents.

### 2.5.4 Other measurements of soil strength

Other instruments that may be used to measure soil strength include shear vanes and shear boxes. The limiting values for these are dependent on the design and size of the shear vanes. Limiting values for the shear vane for the germination and emergence of a wheat plant are described by Lloyd and Collis-George (1982) and Collis-George and Yoganathan (1985):

- 90 (sandy loam) to 390 kPa (clay) for germination depending on texture
- 70 (sandy loam) to 290 kPa (clay) for root elongation depending on texture
- 50 (sandy loam) to 220 kPa (clay) for coleoptile elongation depending on texture
- 20 (sandy loam) to 100 kPa (clay) for emergence depending on texture.

For interpretation of soil strength for engineering purposes see Section 3.5.

### 2.5.5 Key references

Marshall and Holmes (1979); Anderson *et al.* (1980); Lloyd and Collis-George (1982); ASAE (1983); Collis-George and Yoganathan (1985); Passioura (1991); Hunt and Gilkes (1992); Cass (1999).

## 2.6 Aggregate stability

### 2.6.1 Aggregate tests

Aggregate stability refers to the stability of soil structural units (aggregates) when immersed in water. Instability may be indicated by slaking or clay dispersion (see Emerson 1967, 1991). A soil with low aggregate stability is likely to be compact and poorly structured, or be susceptible to tunnelling if used in earthworks.

More recently the Aggregate Stability to Water Test (ASWAT) has been developed by Field *et al.* (1997). This test is based on the Emerson Test and uses similar subdivisions to those in Table 2.24 but is based on 10 minute and two hour readings of dispersion. This is much shorter than the 20 hour readings in the Emerson Test and makes it useable in the field. It uses a scoring system.

The sub-classes of the Emerson Test are defined in Geeves *et al.* (2007a) and are as below:

1. Slight milkiness immediately adjacent to the aggregate.
2. Obvious milkiness, less than 50% of the aggregate affected.
3. Obvious milkiness, more than 50% of the aggregate affected.
4. Total dispersion, leaving only sand grains.

**Table 2.24.** Emerson aggregate test

This is a measure of soil dispersibility or soil structural stability. The following general levels of dispersibility are assigned.

Dispersibility	Emerson aggregate classes	Probable score for the ASWAT test (Field <i>et al.</i> 1997)
Very high	1 and 2 (3)	12–16
High	2 (2)	10–12
High to moderate	2 (1)	9–10
Moderate	3 (4) and 3 (3)	5–8
Slight	3 (2), 3 (1) and 5	0–4
Negligible/aggregated	4, 6, 7, 8	0

Source: Charman (1978); Field *et al.* (1997).

**Table 2.25.** Applications of Emerson aggregate test

\*, amount of susceptibility depends on permeability and resistance to cracking and slumping; \*\*, laboratory tests need to be carried out to determine suitability for earthworks or requirements for ameliorants; \*\*\*, if total dispersed clay (approximate clay percentage  $\times$  dispersion percentage) falls below 5%, the material is likely to leak if used for earthworks.

Class 1	aggregates most certainly indicate high tunnelling susceptibility
Class 2	aggregates indicate some degree* of tunnelling susceptibility
2(1)	desirable for water storage structures to ensure sealing
2(2)	unstable**
2(3)	unstable**
Class 3	aggregates generally stable and indicate a more desirable material for conservation earthworks. (If surface soils containing Class 3 aggregates are cultivated, crusting may become a problem.)
3(1)	most suitable for earthworks
3(2)	most suitable for earthworks
3(3)	**
3(4)	**
Class 4***	aggregated materials may not hold water in a dam, depending on particle size distribution and degree of dispersion
Class 5***	aggregated materials may not hold water in a dam, depending on particle size distribution and degree of dispersion
Class 6	aggregated materials unlikely to hold water in a dam

Source: Crouch *et al.* (2007).

### 2.6.2 Dispersion percentage

The dispersion percentage is the ratio of soil material less than 0.005 mm after limited mechanical dispersion v. the total material less than 0.005 mm after extended mechanical dispersion and the addition of a dispersant. It is expressed as a percentage and estimates the proportion of clay material dispersed. The method is described in Crouch *et al.* (2007) and Australian Standards Association (1980). The dispersal index is the inverse of this multiplied by 100 and has been used to interpret the potential for dispersion in relation to earthworks (see Ritchie 1963) (see Table 2.26).

These ratings are very general only, and account needs to be taken of particle size distribution of the soil for a complete interpretation of the test in relation to *i*, tunnelling susceptibility in Section 3.3.1, and *ii*, turbidity.

**Table 2.26.** Ratings for dispersion percentages

Dispersion percentage (%)	Dispersal index ratio	Ratings
<6	>16	negligible/aggregated
6–30	3.0–16	slight
30–50	2.0–3.0	moderate
50–65	1.5–2.0	high
>65	<1.65	very high

Source: Crouch *et al.* (2007).

### Calculations

To calculate the Dispersion Percentage (DP):

$$\text{Dispersion percentage (\%)} = 100 \times (\text{RL} - \text{RW}) / (\text{RP} - \text{RD})$$

where RL is the hydrometer reading of soil suspension without dispersant and limited mechanical dispersion (g/L); RP is the hydrometer reading of soil suspension with dispersant and prolonged mechanical dispersion (g/L); RW is the hydrometer reading of deionised water (g/L); RD is the hydrometer reading of deionised water plus dispersant (g/L).

Report the dispersion percentage results to the nearest whole number and in conjunction with the particle size analysis of the soil.

### 2.6.3 Implications of aggregate stability ratings for agriculture

Class 1 and 2 surface soils disperse on wetting and readily form a crust.

If surface soils containing Class 3 aggregates are cultivated when they are wet, or are subjected to water drop impact from sprays or rain, then the clay present is liable to disperse when water is applied to the surface resulting in crusting and possibly reduced germination of crops (see Emerson 1991). Dispersion of surface soils can be prevented by applying gypsum (see Abbot and McKenzie 1986). Recent findings suggest that lime may also be useful to treat sodic surface soils (see McKenzie *et al.* 1993 and Valzano *et al.* 2001).

### 2.6.4 Tunnelling susceptibility

See Earthworks in Section 3.3.

### 2.6.5 Exchangeable sodium percentage (ESP)

See Section 5.10.

### 2.6.6 Water stable aggregates/wet sieving

Wet sieving of soil aggregates is a test used to determine the stability of a soil to rapid wetting or raindrop impact. A variety of methods are used (Kemper and Rosenau 1986).

A general interpretation for a test under the following conditions is given in Table 2.27:

- 1–2 mm soil aggregates are tested
- wetting is by slow wetting and then immersion
- a 0.25 mm sieve is used to collect stable aggregates
- aggregates are dipped or immersed in water at a rate of 30 r.p.m. for a period of 30 minutes.

**Table 2.27.** Rating of results for determining water stable aggregates using wet sieving

1–2 mm stable aggregates (%)	Rating
<10	very low
10–20	low
20–30	moderate
>30	high

This is the percentage of 1–2 mm aggregates that are stable to wetting.

The above ratings should be used as a guide only.

### 2.6.7 Field indicators of soil structure decline

There are a number of ‘paddock’ indicators of soil structure decline that can be easily observed. The best way to make these observations is to look at the area suspected of being affected by soil structure decline and compare it with an area of similar soil type that may have better soil structure (Murphy and Allworth 1991).

1. *Rill and sheet erosion.* Soil structure decline leads to increased runoff and low resistance to erosion. This increases rill and sheet erosion.

2. *Surface crusts.* Severe surface crusts develop in soils showing soil structure decline. The crusts reduce infiltration and can restrict seedling emergence if they become dry.

3. *Cloddiness.* After a single cultivation, ‘bricklike’ clods are formed and further cultivation is required to produce a suitable seedbed. (This should not be confused with clods held together by grasses in soils coming out of pasture.)

4. *Specific plant indicators.* In southern NSW, for example, toad rush (*Juncus bufonius*) can be an indicator of soil structure decline. It grows where water has ponded on the surface.

5. *Ponding.* Water ponding after relatively light rain or remaining ponded for several hours after rain can indicate soil structure decline.

6. *Hard surface.* Soil structure decline is indicated by a very hard surface when the soil dries out. The depth of penetration of a falling mattock or pick can be used to test this.

7. *Poor infiltration.* After the first rains following a dry spell, take a shovel and dig down to see how far the rain has infiltrated. Compare soils under pasture with soils of different cultivation histories.

8. *Presence of organic matter.* A degraded soil tends to be brittle and paler in colour. Better soil structure in the same soil is indicated by a darker colour, due to organic matter, and the more friable nature of the soil.

## 2.6.8 Organic binding agents in soils

**Table 2.28.** Summary of the actions of organic agents in the soil and the processes that lead to increased aggregate stability at different scales (Adapted from Haynes and Beare 1996; Cambardella 2002)

Aggregating agents	Aggregation process	Major scale of aggregation
Humic substances	form strong bonds with mineral components	microaggregates
Polysaccharides	gelatinous gluing agents	both micro- and macroaggregates
Plant roots	enmesh soil aggregates, increasing their stability exude polysaccharides	macroaggregates
Fungal hyphae	enmesh soil aggregates, increasing their stability exude polysaccharides	macroaggregates
Earthworms	mix organic matter and clay colloids together mix decaying detritus with the bulk soil	macroaggregates

## 2.6.9 Key references

Kemper and Rosenau (1986); Emerson (1967, 1991); Charman (1978); Tisdall and Oades (1982); Murphy and Allworth (1991); Crouch *et al.* (2007); Geeves *et al.* (2007a).

## 2.7 Water repellence

### 2.7.1 Water repellence

Water repellence is a natural condition of the soil that prevents it from wetting up. It is associated with high levels of organic matter and residues from native plants. The methods for determining water repellence are described in King (1981) and Carter (2002).

Methods of determination of water repellence (King 1981):

- the water drop method (see Table 2.29)
- ethanol test (see Table 2.30)
- infiltration ratio (see Table 2.31).

Table 2.29. Interpretation of water drop test

Time for water drop to infiltrate (s)	Degree of water repellence
<1	not significant
1–10	very low
10–50	low
50–260	moderate
>260	moderate to very severe

Source: King (1981).

Table 2.30. Interpretation of ethanol test

\*, molarity of a drop of ethanol solution to infiltrate within 10 seconds.

Molarity (M) of a drop of ethanol solution*	Degree of water repellence
<1.0	low
1.0–2.2	moderate
2.2–3.0	severe
>3.0	very severe

Source: King (1981); Carter (2002).

Table 2.31. Interpretation of infiltration ratio

\*, values up to 1000 have been recorded.

Infiltration ratio	Rating
<2	not significant to very low
2–5	low
5–15	moderate
15–25	severe
>25*	very severe

Source: Murphy (1986).

The ratio of infiltration rates using water and an aqueous solution of soil wetting agents can be used as a guide to the degree of water repellence.

The infiltration ratio, IR, is given by the following equation:

$$IR = I_a/I_w$$

where  $I_a$  is the infiltration rate with the wetting agent (1% solution), and  $I_w$  is the infiltration rate with water alone.

### 2.7.2 Key references

King (1981); Murphy (1986); Carter (2002).



# 3

## Soil engineering properties

### 3.1 Unified soil classification system (USCS)

#### 3.1.1 General scheme

The USCS (Unified Soil Classification System) is based on identification of soils according to particle size, gradation, plasticity index and liquid limit (see Table 3.1). It is a simple classification for engineering purposes and can be used for the design of earthworks and small dams (US Bureau of Reclamation 1960). (This classification is not a substitute for engineering tests where site-specific accurate data is required.)

**Table 3.1.** USCS classification

USCS, Unified Soil Classification System. Particle sizes for the USCS classification are described in Section 2.1.3.

USCS classification	Description
GW	well-graded gravels, gravel-sand mixtures, little or no fines
GP	poorly graded gravels, gravel-sand mixtures, little or no fines
GM	silty gravels, poorly graded gravel-sand-silt mixtures
GC	clayey gravels, poorly graded gravel-sand-clay mixtures
SW	well-graded sands, gravelly sands, little or no fines
SP	poorly graded sands, gravelly sands, little or no fines
SM	silty sands, poorly graded sand-silt mixtures
SC	clayey sands, poorly graded sand-clay mixtures
ML	inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity
CL	inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
OL	organic silts and organic silt-clays of low plasticity
MH	inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
CH	inorganic clays of high plasticity, fat clays
OH	organic clays of medium to high plasticity
Pt	peat and other highly organic soils

Source: Casagrande (1947); US Bureau of Reclamation (1960).



### 3.1.2 Summary of field identification tests

<b>Coarse grained soils</b> More than half of the material (by weight) is individual grains visible to the naked eye.	<b>Gravelly soils</b> More than half of coarse fraction is larger than 6 mm		<b>Clean gravels</b> Will not leave a stain on a wet palm		Substantial amounts of all grain particle sizes		GP
			<b>Dirty gravels</b> Will leave a stain on a wet palm		Predominately one size or a range of sizes with some intermediate sizes missing		
	<b>Sandy soils</b> More than half of coarse fraction is smaller than 6 mm		<b>Clean sands</b> Will not leave a stain on a wet palm		Nonplastic fines		
					Plastic fines		
			<b>Dirty sands</b> Will leave a stain on a wet palm		Wide range in grain size and substantial amounts of all grain particle sizes		ML
					Predominately one size or a range of sizes with some intermediate sizes missing		
<b>Dirty sands</b> Will leave a stain on a wet palm		Nonplastic fines		CL			
		Plastic fines		MH			
<b>Fine grained soils</b> More than half of the material (by weight) is individual grains not visible to the naked eye.	<b>Ribbon</b>	<b>Liquid limit</b>	<b>Dry crushing strength</b>	<b>Dilatancy reaction</b>	<b>Toughness</b>	<b>Stickiness</b>	
	None	<50	None to slight	Rapid	Low	None	ML
	Weak	<50	Medium to high	None to very slow	Medium to high	Medium	CL
	Strong	>50	Slight to medium	Slow to none	Medium	Low	MH
	Very strong	>50	High to very high	None	High	Very high	CH
<b>Highly organic soils</b>	Readily identified by colour, odour, spongy feel and frequently by fibrous texture						OL OH PT

Fig. 3.1. Summary of field identification tests.

### 3.1.3 Engineering characteristics of Unified Soil Classification System groups

The general engineering characteristics of soils based on the USCS is summarised in US Bureau of Reclamation (1960), Harding (1991) and Hicks (2007). When soils are used as construction materials in any type of fill or embankment they nearly always require compaction to prevent settlement and to reduce permeability. For any type of soil there is a limit to the density that can be achieved by compaction under a given effort. This maximum density can be attained only at a particular moisture content known as the *optimum moisture content*. Below the optimum moisture content the soil fabric resists rearrangement of the particles into a state of close-packing, whereas above it the presence of water in the voids inhibits the achievement of closer inter-granular contact. In many instances with small earth dams it will not be possible to achieve the maximum dry density, and permeabilities will be substantially higher than those indicated in Table 3.2. The maximum dry densities outlined in Table 3.2 will only be achieved by careful control of the moisture content and compactive effort during construction. Engineering suitability ratings based on Unified Soil Classification groups are shown in Table 3.3.

**Table 3.2.** Engineering characteristics of USCS groups

\*, insufficient data; \*\*, provided soils are not highly aggregated;  $\pm$  90% confidence limits; Co, strength of soil placed at Proctor maximum dry density; Csat, strength of soil placed at Proctor maximum dry density and then saturated; USCS, Unified Soil Classification System.

USCS	Proctor compaction		Permeability** at Proctor maximum compaction (mm/h.)	Compressibility		Shearing strength	
	Maximum dry density g/cm <sup>3</sup>	Optimum moisture (%)		at 138 kPa	at 345 kPa	Co kPa	Csat kPa
GW	>1.90	<13.3	936 $\pm$ 450	1.4	(*)	(*)	(*)
GP	>1.76	<12.4	2232 $\pm$ 1188	0.8	(*)	(*)	(*)
GM	>1.83	<14.5	0.01	1.2	3.0	(*)	(*)
GC	>1.84	<14.7	0.01	1.2	2.4	(*)	(*)
SW	1.91 $\pm$ 0.08	13.3 $\pm$ 2.5	(*)	1.4 $\pm$ *	(*)	39.3 $\pm$ 4.1	(*)
SP	1.76 $\pm$ 0.03	12.4 $\pm$ 1.0	0.5	0.8 $\pm$ 0.3	(*)	22.8 $\pm$ 6.2	(*)
SM	1.83 $\pm$ 0.02	14.5 $\pm$ 0.4	0.3 $\pm$ 0.16	1.2 $\pm$ 0.1	3.0 $\pm$ 0.4	51.0 $\pm$ 6.2	20.0 $\pm$ 6.9
SM-SC	1.91 $\pm$ 0.02	12.8 $\pm$ 0.4	0.03 $\pm$ 0.02	1.4 $\pm$ 1.0	2.9 $\pm$ 1.0	50.3 $\pm$ 21.4	14.5 $\pm$ 5.5
SC	1.84 $\pm$ 0.02	14.7 $\pm$ 0.4	0.01 $\pm$ 0.007	1.2 $\pm$ 0.2	2.4 $\pm$ 0.5	75.1 $\pm$ 15.2	11.0 $\pm$ 6.2
ML	1.65 $\pm$ 0.02	19.2 $\pm$ 0.7	0.02 $\pm$ 0.008	1.5 $\pm$ 0.2	2.6 $\pm$ 0.3	66.9 $\pm$ 10.3	9.0 $\pm$ (*)
ML-CL	1.74 $\pm$ 0.03	16.8 $\pm$ 0.7	0.005 $\pm$ 0.003	1.0 $\pm$ 0.0	2.2 $\pm$ 0.0	63.4 $\pm$ 16.5	22.0 $\pm$ (*)
CL	1.73 $\pm$ 0.02	17.3 $\pm$ 0.3	0.003 $\pm$ 0.001	1.4 $\pm$ 0.2	2.6 $\pm$ 0.4	86.9 $\pm$ 10.3	13.1 $\pm$ 2.1
MH	1.31 $\pm$ 0.06	36.3 $\pm$ 3.2	0.005 $\pm$ 0.004	2.0 $\pm$ 1.2	3.8 $\pm$ 0.8	72.4 $\pm$ 29.6	20.0 $\pm$ 9.0
CH	1.51 $\pm$ 0.03	25.5 $\pm$ 1.2	0.002 $\pm$ 0.002	2.6 $\pm$ 1.3	3.9 $\pm$ 1.5	102.7 $\pm$ 33.8	11.0 $\pm$ 5.9

Adapted from US Bureau of Reclamation (1960) and Hicks (2007).

**Table 3.3.** Engineering suitability ratings based upon Unified Soil Classification groups  
n/a, not applicable; USCS, Unified Soil Classification System.

Unified soil classification typical names	USC group symbol	Source of borrow			Resources	Suitability for:					
		Embankments		Fill		Clean sand/ gravel	Road sub-grade	Building foundations	Slope stability	Trenching/ tunnelling	Septic tanks
		Water retaining	Non-water retaining								
Well-graded gravels, gravel-sand mixtures, little or no fines	GW	unsuitable	excellent	excellent	good	excellent	excellent	(excellent)	shoring	good	average
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	unsuitable	average	excellent	good	excellent	excellent	(average)	shoring	excellent	unsuitable
Silty gravels, poorly graded gravel-sand-silt mixtures	GM	unsuitable	average	good	average	excellent	excellent	(average)	shoring	average	average
Clayey gravels, poorly graded gravel-sand-clay mixtures	GC	suitable	average	good	poor	excellent	excellent	(average)	good	unsuitable	excellent
Well-graded sands, gravelly sands, little or no fines	SW	unsuitable	excellent	excellent	good	good	excellent	(average)	shoring	good	average
Poorly graded sands, gravelly sands, little or no fines	SP	unsuitable	average	good	good	good	excellent	(excellent)	shoring	good	unsuitable
Silty sands, poorly graded sand-silt mixtures	SM	suitable (with compaction)	average	average	average	average	good (density important)	(average)	mostly good (but shoring may be required)	poor	poor
Clayey sands, poorly graded sand-clay mixtures	SC	suitable	average	average	poor	average	good (density important)	(average)	good	unsuitable	good

Unified soil classification typical names	USC group symbol	Source of borrow			Resources	Suitability for:					
		Embankments		Fill		Clean sand/ gravel	Road sub-grade	Building foundations	Slope stability	Trenching/ tunnelling	Septic tanks
		Water retaining	Non-water retaining								
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	unsuitable	poor	average	n/a	average	good (liquefaction problem)	(average)	shoring	average	unsuitable
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	CL	suitable (erosion protection required)	good	average	n/a	average	average (swelling?)	(poor)	good	unsuitable	poor
Organic silts and organic silt-clays of low plasticity	OL	unsuitable	unsuitable	poor	n/a	average	poor (swelling?)	(good)	shoring	poor	unsuitable
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic soils	MH	unsuitable	poor	poor	n/a	poor	unsuitable (swelling?)	(unsuitable)	shoring	average	unsuitable
Inorganic clays of high plasticity, fat clays, silty soils, elastic soils	CH	suitable (erosion protection?)	average	unsuitable	n/a	poor	poor (swelling?)	(poor)	good	unsuitable	unsuitable
Organic clays of medium to high plasticity	OH	unsuitable	unsuitable	unsuitable	n/a	unsuitable	unsuitable (swelling?)	(average)	shoring	unsuitable	unsuitable
Peat or other highly organic soils	PT	unsuitable	unsuitable	unsuitable	n/a	unsuitable	unsuitable (swelling?)	(unsuitable)	shoring	average	unsuitable

Source: Finlayson (1982).

Note: These recommendations are based on the construction of earthworks with adequate access to compaction and engineering equipment. They are based solely on the USCS classification, which does not take account of the full effects of particle size, dispersion or the conditions under which soil conservation earthworks are constructed. This then is not a DLWC based set of recommendations for the construction of soil conservation earthworks. These are presented in Section 3.3.

### 3.1.4 Key references

Casagrande (1947); US Bureau of Reclamation (1960); Harding (1991); Hicks (2007).

## 3.2 General levels of interpretation for plasticity index\*, liquid limit\* and uses

(\*, moisture content and climatic data must also be considered in interpreting results.)

### 3.2.1 Plasticity index

Plasticity index represents the range of water contents across which the soil is in a plastic state (see Table 3.4). Soils with a low plasticity index can change from a solid to a liquid with little change in moisture content. These soils may be prone to mass movement (Hicks 2007).

**Table 3.4.** Ratings for compressibility and shrink-swell potential based on plasticity index (increasing degree from low to very high)

Rating	Plasticity index (%)
Low	<25
Medium	25–35
High	35–45
Very high	>45

Source: Public Works Department (1977).

### 3.2.2 Liquid limit

Liquid limit is the moisture content at which a soil passes from a plastic to a liquid state (see Table 3.5). It is directly proportional to the compressibility of a soil and hence its ability to support a load and its trafficability when wet. It can also indicate shrink-swell potential (Mills *et al.* 1980; Hicks 2007).

**Table 3.5.** Ratings for compressibility and shrink-swell potential based on liquid limit (increasing degree from low to very high)

Rating	Liquid limit (%)
Low	<45
Medium	45–55
High	55–75
Very high	>75

Source: Public Works Department (1977); Mills *et al.* (1980).

**Table 3.6.** Plasticity rating of USCS groups

USCS, Unified Soil Classification System; \*, unsuitable for embankments; \*\*, unsuitable for embankments either water or non-water retaining; \*\*\*, mass movement potential, unsuitable for building foundations, unsuitable for unsealed roads, unsuitable for septic tanks.

Plasticity rating	USCS
Low plasticity to non-plastic	CL–ML
Low plasticity	ML*
Low plasticity	SM
Low plasticity	OL**
Moderately plastic	CL–CH
Highly plastic	OH***
Highly plastic	MH***
Highly plastic	CH***
Highly plastic	CH–CL

Source: Craze and Hicks (1987).

### 3.2.3 Key references

US Bureau of Reclamation (1960); Mills *et al.* (1980); Finlayson (1982); Craze and Hicks (1987); Hicks (2007).

## 3.3 Earthworks

### 3.3.1 General interpretations

The following recommendations are based on experience with small farm dams in central and eastern New South Wales. These dams are usually less than 5000 m<sup>3</sup> in capacity and have a top water level of less than 3 m above the original ground surface at the upstream side of the wall. Often soil conservation earthworks are built in less than ideal engineering conditions because the equipment and time to achieve optimum compaction levels cannot be obtained economically. This makes dispersion and tunnelling susceptibility a greater hazard than for structures built under more rigorous engineering conditions. The recommendations presented in Table 3.2 and Table 3.3 take these construction conditions into account.

Soil properties are continuously variable and the limits set are not fixed divisions between groups. Interpretation will often be a compromise between two recommendations.

Soil will vary within a structure site. The relative proportions of the different soil materials need to be considered and construction technique planned accordingly.

The recommendations are based on a well-graded soil. Soil materials that do not have an equal distribution of particle sizes (grading gaps) require special consideration.

The value limits used in these recommendations have been set for typical farm situations where the consequence of failure only involves loss of stored water. Where the consequence of failure as described by Fietz (1969) is higher (such as damage to roads or buildings, or loss of life), limits for batter grades, use of ameliorants and compaction levels should be appropriately modified.

A full set of recommendations is given in Crouch *et al.* (2007) but an alternative, closely related set of recommendations is given in Table 3.7.

**Table 3.7.** Recommendations for small farm dams from soil test data

USCS, Unified Soil Classification System; EAT, Emerson Aggregate Test.

USCS class	Clay (%)	Clay + silt (%)	Silt + fine sand	EAT class	Dispersion (%) <5 µm	Volume expansion (%)		
						0–20	20–30	>30
						Linear shrinkage (%)		
						0–12	12–17	>17
	<10	<20				I*	K	K
CH	>40			1	65–100	D	F	H and F
				1 or 2	50–65	B	D	G and F
				2 or 3	30–50	B	D	F
				3	10–30	A	G	H
				4–6	0–10	C	C	H
CH	<40			1	65–100	D	E	F
				1 or 2	50–65	D	D	F
				2 or 3	30–50	B	D	E
				3	10–30	A	G	H
				4–6	0–10	C	C	H
MH	<25			1	65–100	E	E	F
				1 or 2	50–65	D	D	F
				2 or 3	30–50	B	D	E
				3	10–30	A	B	H
				4–6	0–10	C	C	H
MH	>25			1	65–100	D	E	F
				1 or 2	50–65	D	D	E
				2 or 3	30–50	B	G	H
				3	10–30	A	G	H
				4–6	0–10	C	G	H
CL			<50	1	65–100	D	D	K
				1 or 2	50–65	D	D	K
				2 or 3	30–50	B	B	K
				3	10–30	A	A	K
				4–6	0–10	C	A	K
CL			>50	1 or 2	30–100	D	E	K
				3	10–30	B	B	B
				4–6	0–10	C	C	K
ML				1	65–100	E	E	K
				1 or 2	50–65	D	D	K
				2 or 3	30–50	B	B	K
				3	10–30	A	A	K
				4–6	0–10	C	A	K
SC				1	65–100	D	E	K
				1 or 2	50–65	D	D	K
				2 or 3	30–50	B	B	G

USCS class	Clay (%)	Clay + silt (%)	Silt + fine sand	EAT class	Dispersion (%) <5 µm	Volume expansion (%)		
						0–20	20–30	>30
						Linear shrinkage (%)		
						0–12	12–17	>17
GC				3	10–30	B	A	K
				4–6	0–10	C	A	K
				1	65–100	E	J	K
				1 or 2	50–65	D	D	K
				2 or 3	30–50	B	B	K
				3	10–30	B	B	K
SM and GM				4–6	0–10	C	A	K
				1 or 2	30–100	J	K	K
				3	10–30	B and I	K	K
SW & SP				4–6	0–10	I	K	K
					30–100	J	K	K
GW & GP					0–30	I	K	K
OL, OH & Pt				All	0–100	J	J	J

Adapted from Crouch *et al.* (2007).

### Interpretation of Table 3.7

A. Suitable for normal use. Take care to achieve good compaction, preferably with moist soil. If the soil is dry (cannot be moulded), reduce layer thickness to less than 15 cm. Minimum batter grades 1:2.5 upstream, 1:2 downstream, except for CH and MH classifications when they should be decreased to 1:3 and 1:2.5, respectively.

B. This material is stable and impervious when well compacted, to at least 85% of Proctor maximum dry density. To achieve this, the soil should be close to the optimum moisture content for the compaction plant, be placed in layers less than 15 cm thick, and be compacted with four complete passes of a crawler tractor or roller. For crawler tractors, the soil should be sufficiently moist to be made into a thread 10 mm thick, but not moist enough to be rolled thinner than 3 mm without breaking. Minimum batter grades are 1:3 upstream, and 1:2.5 downstream.

C. Aggregated material that may not hold water. Compact with at least four passes of a sheep'sfoot roller when the soil is slightly wetter than the optimum moisture content for compaction (can be rolled into a 3 mm diameter thread). Use a vibrating roller for dry soils. An ameliorant (STPP or sodium carbonate) is probably required. If the Emerson Aggregate Test (EAT) is Class 6 or the dispersion percentage is <6, then the dam is likely to leak. The dam will need to be sealed with better clay or treated with an ameliorant such as STPP or sodium carbonate to induce dispersion.

D\*. This soil is highly susceptible to tunnelling or piping failure. It must be well compacted throughout to reduce permeability and saturation settlement. If it is drier than the optimum moisture for compaction, gypsum or hydrated lime should be used at 1 t/750 m<sup>3</sup> of wall to reduce dispersion. The soil should be compacted to at least 85% of Proctor maximum dry density by ensuring the correct moisture content



(see recommendation B), placing it in layers less than 15 cm thick and rolling with at least four complete passes of the plant. For additional stability, the structure should be designed to hold no more than 1 m of water against the wall, and batter grades should be decreased to 1:3.5 upstream and 1:3 downstream.

E\*. This soil is very susceptible to tunnelling or piping failure. In addition to recommendation D, the structure must hold no more than 1 m depth above the original ground surface at the upstream side of the wall, and not be subject to more than 0.3 m a day of drawdown (trickle pipes must not be more than 0.3 m below the top water level). Gypsum or hydrated lime at the rate of 1 t/750 m<sup>3</sup> of wall should be incorporated in the upstream side of the wall. The upstream batter grades should be decreased to 1:4.

F\*. This soil is very susceptible to tunnelling or piping failure. Due to the high shrink-swell potential, batter grades must be decreased. In addition to recommendation D, freeboard must be increased to at least 1 m above surcharge level, and hydrated lime or gypsum should be applied at rates determined in the laboratory. Batter grades should be decreased to 1:4 upstream and 1:3 downstream.

G. The high shrink-swell potential of this soil can result in cracks extending through the wall below the top water level. To reduce this possibility, a compact central core (at least 85% Proctor maximum compaction) must be obtained by constructing when the soil is sufficiently moist to be rolled into a 10 mm diameter thread, but not moist enough to roll to 3 mm without breaking. The freeboard must be increased to at least 1 m above surcharge to prevent surface cracks extending below the waterline. Recommended batter grades are 1:3.5 upstream and 1:3 downstream. The structure must be designed to retain sufficient water to keep the wall moist and minimise development of cracks.

H. This soil is not recommended for earthworks unless all the following precautions can be implemented. The central core must be well compacted, preferably with a vibrating sheepsfoot roller, to obtain a density of at least 85% Proctor maximum as determined in the laboratory. The settled freeboard must be increased to 1 m above surcharge level and batter grades should be at least 1:4 upstream and 1:3 downstream.

I\*. Pervious. This soil is not recommended for general use in earthworks, but may be used in a zoned embankment or sealed with bentonite or a plastic liner. Recommended batter grades are 1:3 upstream and 1:3 downstream.

J. This soil is not recommended for use in earthworks.

K. Topsoils are sometimes found with these attributes. Any subsoils with these attributes are usually unsuitable for use in construction of earthworks.

\*, Tunnelling or leaking may be controlled with the use of plastic liners. Before you use plastic liners, we recommend you contact a local advisory officer or consultant who is experienced in their use.

A full set of recommendations for earthwork construction is given in Crouch *et al.* (2007); a brief summary of these is given in Table 3.8. For a formal interpretation of soil test results the user is referred to Crouch *et al.* (2007).

**Table 3.8.** General problems for earthworks in relation to soil tests

USCS, Unified Soil Classification System.

Major problem	Soil property	Soil tests	Remarks
1. Tunnelling or piping	dispersion permeability	dispersion percentage (DP) Emerson aggregate test (EAT) volume expansion (VE) particle size analysis	A combination of high dispersibility and high permeability indicates the most susceptible soils. Most susceptible soils have dispersion percentage >33%, EAT class 1 or 2(3), VE <0, clay 15%–30%, and high fine sand or silt; ML, SM materials.
2. Leaking	aggregation permeability	particle size analysis dispersion percentage	Soils with low fines content or high aggregation are the most susceptible. Most susceptible soils are clay <10%, clay and silt <20%. For clay soils, dispersion percentage <6% or total dispersed clay <5%.
3. Slumping	wet strength	particle size analysis USCS liquid limit and plasticity index	Very dependent on zoning of dam wall, which should overcome most problems. Most susceptible soils are clay <20%, and high silt, fine sand and coarse sand; SM, some SC, ML and MH materials.
4. Cracking	shrink-swell potential	linear shrinkage (LS) volume expansion	Heavy clays have high shrink-swell activity. Most susceptible soils have LS >17% and VE >40%.
5. Optimum moisture content	compaction characteristics	optimum moisture content (OMC)	Compaction of soils wet or dry of the optimum moisture content results in less than optimum compaction. This may or may not be critical, depending on other soil properties. The optimum moisture contents given are usually based on USCS Class.

Source: Murphy (1981).

**Table 3.9.** Relationship between particle size analysis, texture, USCS, dispersion percentage and grading used to predict leaking when soils are used for earthworksUSCS, Unified Soil Classification System; \*, total dispersed clay  $\equiv$  % clay  $\times$  dispersion percentage; \*\*, see Table 3.7 or Crouch *et al.* (2007).

Particle size analysis	Texture	USCS	Dispersion percentage	Grading	Total dispersed clay*	Rating	Earthwork suitability code**
Silt and clay <20%, clay <10%	sands sandy loam fine sandy loam	SM SC	<6	poor	<3%	extremely susceptible (little doubt)	I
Silt and clay 20%–40%, clay <20%	fine sandy loam loam	ML	6–13	good for sandy soils	3%–5%	marginal	A/C
Silt and clay >40%, clay >20%	clay loam clay	CL CH	>13	good	>5%	no concern	A/B

Source: Murphy (1981).

### 3.3.2 Tunnelling susceptibility

Tunnelling susceptibility refers to the likelihood of tunnels forming in a body of soil as a consequence of water flow through the soil. This is also referred to as piping (Sherard and Decker 1977).

There are three requirements to form a tunnel in this way:

- A soil that is easily detached and transported by water flow through the soil. This usually means soil that has a highly dispersible clay or high levels of silt and fine sand.
- A head of water to provide a potential for water flow through the soil.
- A system of cracks or pores that provide a relatively rapid flow path through the body of the soil (see Tables 3.10, 3.11 and 3.12).

Earthworks that pond water (such as dams and banks), can be extremely susceptible to tunnelling or piping because of the presence of a continuous head of water (Ritchie 1963).

Tunnelling may also occur in the field in *in situ* soils as described in Crouch *et al.* (1986). In these cases, tunnelling is usually associated with gullies, roadside batters or poorly drained areas.

**Table 3.10.** Relationship of soil tests to tunnelling susceptibility

DP, dispersion percentage; EAT, Emerson Aggregate Test; PSA, particle size analysis; VE, volume expansion; USCS, Unified Soil Classification System.

DP	EAT	PSA	VE%	USCS	Tunnelling susceptibility	Earthwork suitability code
>33%	1 or 2 (3)	clay 15%–30%, silt and fine sand >50%	<0 or incomplete wetting	SM, CL, ML, MH		
All of the above soil properties occurring together					Extremely susceptible (little doubt).	J, D, E, F
>33%	1 or 2 (3)	clay >30%, or coarse sand >30%	<0 or incomplete wetting	CL, SC		
All of the above soil properties occurring together					Very highly susceptible, but not as critical as in the category above.	D, E
>33%	1 or 2 (3) or 2 (2)	clay 15%–30%, silt and fine sand >50%	<0 or incomplete wetting or low for clay content	SM, CL, ML, MH		
Only some or one of the above soil properties occurring					Highly susceptible. Strong possibility of tunnelling soil.	D, E, J
<33%	2 (1), 3, 4, 5 or 6	clay >30%, silt and fine sand <50%	>0 and correlates well to clay content	CL, CH, SC	Stable material under appropriate construction methods	A, B, C, G, H, D, E, F

Source: Murphy (1981). (Also see Table 3.7 and Crouch *et al.* (2007).)

**Table 3.11.** Dispersive soils classification (geotechnical)

(i)	
Test	Classification
dispersal index	0–2.5 dispersive 2.5–3.0 possibly dispersive >3.0 non-dispersive
(ii)	
Test	Classification
pinhole test	D1 highly dispersive D2 dispersive ND4 possibly dispersive ND3 possibly dispersive ND2 non-dispersive ND1 non-dispersive
(iii)	
Test	Classification
Sherard crumb test	1 non-dispersive 2 possibly dispersive 3 dispersive 4 dispersive

Sources: (i) Ritchie (1963); Public Works Department (1990) (see Section 2.6.1).

(ii) Sherard *et al.* (1976); Australian Standards Association (1984: AS1289.C8.3).

(iii) Sherard *et al.* (1976); Australian Standards Association (1984: AS1289.C8.3).

**Table 3.12.** Predicting slumping of earthworks

Particle size analysis is the main test for predicting slumping. The following scale can be used to determine the susceptibility to slumping in soils for earthworks. USCS, Unified Soil Classification System.

Grading	Particle size analysis		USCS	Rating	Earthwork suitability code
Poor	coarse sand >60%, clay <10%	silt and fine sand >60%, clay <10%	SM, SC, ML	extremely susceptible (little doubt)	I
Poor	coarse sand 50%– 60%, clay 10%–20%	silt and fine sand 50%–60%, clay 10%–20%	SM, SC, ML	highly susceptible	J, I, B, C, D, E
Good	clay >20% and not dispersible		SC, CL, CH	no or little concern	A, B, C

See Table 3.7 and Crouch *et al.* (2007).

### 3.3.3 Key references

Fietz (1969); Sherard and Decker (1977); Murphy (1981); Australian Standards Association (1984); Public Works Department (1990); Crouch *et al.* (2007).

## 3.4 Expansive soils

### 3.4.1 Surface movement potential

Surface movement potential is an estimate of the potential soil shrink and swell movements that may occur with changes in soil moisture content. Surface movement can cause expensive damage to inappropriately designed buildings, roads and underground surfaces. Field indications of expansive soils include (Hicks 2007):

- soils with surface cracks 6 mm or more wide, 300 mm or more deep and at least one crack per square metre
- soils that develop gilgai microrelief
- soils with obvious medium to heavy clay subsoils
- soils with depth greater than 50 cm.

However, not all expansive soils can be identified in this way and soil testing is required using the methods described below.

### 3.4.2 Reactivity classification classes

Standards developed under the former NSW Building Licensing Board included a 'Classification of NSW Soils for Housing', where soils are ranked into five classes depending on their reactivity. These recommendations relate to residential slabs and footings.

The classes are as follows:

*Stable.* Non-cohesive or non-plastic soils, soils with less than 15% of particles finer than 76  $\mu\text{m}$ , and less than 2 m depth of soil above rock.

*Slightly reactive.* Soils with less than 0.5 m of clay above rock, or non-cohesive soils over 2 m deep. The expected maximum surface movement is less than 15 mm.

*Moderately reactive.* The expected maximum surface movement is 15–40 mm.

*Highly reactive.* The expected maximum surface movement is 40–60 mm.

*Extremely reactive.* The expected maximum surface movement is greater than 60 mm.

### 3.4.3 Linear shrinkage

Linear shrinkage is the percentage decrease in the length of a bar of soil dried in an oven from the liquid limit, and it is assessed on a disturbed sample (Australian Standards Association 1977). A high linear shrinkage indicates a large potential shrinkage of the soil mass on drying, and places limitations on the use of the soil as foundations for small buildings (see Table 3.13). McKenzie *et al.* (1994) proposed a quicker method for linear shrinkage for pedological studies, but it does not conform to the Australian Standards methodology.

An estimate of the likely surface movement can be obtained by assessing the reactivity of a site using plasticity index and linear shrinkage. Areas of humid climate include Sydney, Hobart and Brisbane. Because of the dry summers and wet winters, Melbourne, Adelaide and Perth are grouped as arid and semi-arid for the purposes of this classification. The wet winters and dry summers in these latter three cities lead to a wider range of soil moisture conditions during the year (see Table 3.14).

**Table 3.13.** Categories of linear shrinkage

\*, specific design criteria need to be incorporated in building foundations to prevent movement problems.

Category	Linear shrinkage (%)	Expansive rating
Low	0–12	non-critical
Medium	12–17	marginal
High	17–22*	critical*
Very high	>22*	very critical*

Source: Public Works Department (1977); Mills *et al.* (1980); Hicks (2007).

**Table 3.14.** Potential volume change

Potential volume change	Arid to semi-arid climate		Humid climate	
	Plasticity index (%)	Linear shrinkage (%)	Plasticity index (%)	Linear shrinkage (%)
Low	0–15	0–5	0–30	0–12
Medium	15–30	5–12	30–50	12–18
High	>30	>12	>50	>18

Source: Holland (1981).

### 3.4.4 Volume expansion

Volume expansion measures the free swelling of a disturbed soil on wetting from air dry to saturated. A volume expansion of 20–40% indicates a large potential expansion on wetting and subsequent shrinkage on drying, and places limitations on the use of the soil as a foundation for earthworks and small buildings (see Table 3.15).

**Table 3.15.** Ratings for volume expansion

Rating	Volume expansion (%)
Low	<20
Moderate	20–30
High	30–40
Very high	>40

Source: Crouch *et al.* (2007).

Volume expansion may underestimate the potential expansion of a soil in the field because in dispersible soils, the soil may collapse on wetting, actually causing shrinkage. This is a consequence of the very low bulk density of the soil in the volume expansion mould (see Mills *et al.* 1980).

### 3.4.5 Coefficient of linear extensibility (COLE)

The changes in volume and the linear dimensions of soil clods with changes in moisture content have been used to identify expansive soils. In particular the coefficient of linear extensibility (COLE) has been used for this purpose (Grossman *et al.* 1968; McGarry 2002). The changes are also used as a measure of the structural condition of a soil in an agricultural situation, particularly for cotton soils (McGarry and Daniells 1987).

### 3.4.6 Key references

USDA (1972); Public Works Department (1977); Mills *et al.* (1980); McGarry and Daniells (1987); McKenzie *et al.* (1994); Crouch *et al.* (2000); Hicks (2007); McGarry (2002).

## 3.5 Engineering interpretation of soil strength

### 3.5.1 Introduction

The determination of soil strength plays a major role in the engineering assessment of load bearing capacity, soil compressibility, safe slope inclinations and trafficability. For the purpose of evaluating strength, soils are divided into two groups, cohesive and cohesionless.

### 3.5.2 Strength of cohesive soils

Cohesive soils are plastic soils. They are clays or soils that contain a sufficient clay fraction to enable them to be rolled to a thread or moulded to shape when moist. The strength of such soils is categorised on the basis of actual measurements or simple field tests. Field measurement is carried out using shear vanes, penetrometers or compression testers. Laboratory unconfined or triaxial compression tests may be conducted on samples to measure strength. Strength should only be assessed when the soil is moist and saturated because cohesive soils gain considerable strength as they dry out (see Table 3.16).

**Table 3.16.** Categories of strength of cohesive soils  
UCS, unconfined compressive strength.

Category	UCS (kPa)	Density (g/cm <sup>3</sup> )	Field identification
Very soft	0–25	1.5–1.6	easily penetrated by fist
Soft	25–50	1.6–1.8	easily penetrated a few centimetres by thumb
Firm	50–100	1.7–2.0	can only be penetrated 1–2 cm with considerable effort by thumb
Stiff	100–200	1.8–2.1	can be indented with thumb but not penetrated
Very stiff	200–400	1.9–2.2	readily indented with thumbnail
Hard	>400	1.9–2.3	only just indented with thumbnail, with difficulty

Adapted from Bowles (1985).

### 3.5.3 Strength of cohesionless soils

Cohesionless soils are non-plastic soils or soils that cannot be moulded to shape. They include gravels, sands and non-plastic silts as well as mixed textured soils with a minor clay fraction. The strength of such soils is controlled to a large extent by their relative density. Relative density is a measure on a scale of 0–1 (0, loosest possible state for the soil; 1, most dense). The density of a soil in the field will be between these extremes, and its relative density is a measure of where it lies on this scale. Relative density is most commonly measured by penetrometer tests, particularly those that correlate with the Standard Penetration Test (SPT) number *N* as described in AS 1289. The Cone

Penetration Test (CPT) is also used (De Ruiter 1971). Simple field tests, such as assessing the resistance to driving a pointed 50 mm square stake with a 5 kg hammer, are also used (see Tables 3.17–3.18).

**Table 3.17.** Categories of strength of cohesionless soils

Category	Relative density	Density (g/cm <sup>3</sup> )	Force (N)	Cone resistance (MPa)	Field identification
Loose	<0.35	1.4–1.8	<10	<4	stake easily driven
Medium	0.35–0.65	1.7–2.0	10–30	4–12	stake driven with some effort
Dense	>0.65	1.8–2.2	>30	>12	stake cannot be driven far

**Table 3.18.** Engineering properties related to strength

The table gives data on typical values for safe bearing pressure under footings, level of soil compressibility and trafficability for cohesive and cohesionless soils.

Category	Safe bearing pressure (kPa)	Compressibility	Trafficability
<b>a. Cohesive soils</b>			
Soft to firm	50–100	high	poor, trucks bog in soft deep ruts in firm soil
Stiff to very stiff	100–200	moderate-low	good, slight rutting
Hard	>300	very low	very good, no rutting
<b>b. Cohesionless soils</b>			
Loose	<100	high	poor, 4WD required, laden trucks bog
Medium	200	low	satisfactory if 4WD, deep rutting if laden
Dense	>300	very low	good, surface rutting only

Source: Sowers (1965); Winterbottom and Fang (1974); Canadian Engineering Society (1978).

### 3.5.4 Key references

De Ruiter (1971).

### 3.5.5 Further reading

Australian Standards Association (1984). *Determination of Pinhole Dispersion of a Soil AS1289, C8.3.*





# 4

## Soil erodibility and erosion hazard

### 4.1 Erosion types

The principal types of erosion are:

(i) *Water erosion.* An erosion process in which soil is detached and transported from the land by the action of rainfall, runoff, seepage and/or ice. Types of water erosion include splash, sheet, rill, gully, streambank and tunnel erosion (see Houghton and Charman 1986; Rosewell *et al.* 2007). A computer program that models sheet and rill erosion at the paddock scale is available in Rosewell (1993). This program is used to select land management practices that minimise soil erosion.

(ii) *Wind erosion.* An erosion process in which soil is detached and transported from the land surface by the action of wind. Transport of windblown particles occurs by suspension, saltation or surface creep (see McTainsh and Leys 1993; Rosewell *et al.* 2007).

### 4.2 Erosion hazard

#### 4.2.1 Erosion hazard for water

The water erosion hazard of a parcel of land refers to its susceptibility to water erosion. It depends on a number of factors including (Rosewell *et al.* 2007):

- climate
- slope
- hydrological conditions in relation to landform (runon and runoff)
- soil erodibility
- land use.

**Table 4.1.** Degrees of erosion hazard

These degrees of erosion hazard have been defined by Morse *et al.* (1982) and Houghton and Charman (1986).

Class of erosion hazard	Description of classes
Slight	The combination of slope, runoff/runon and erodibility is such that no appreciable erosion damage will take place.
Moderate	Significant short-term erosion will occur as a result of the combination of slope, soil erodibility, and runoff/runon factors. Control can be obtained with structural works, topsoiling, vegetative techniques and by phasing development.
High	Major erosion, and in some cases long-term erosion, can be expected to take place. Control of this erosion will require the adoption of intensive soil conservation works.
Very high	Major short-term and long-term erosion losses can be expected with this land. The combination of slope, soil erodibility and runoff/runon ratings make intensive soil conservation works necessary.
Extreme	Even with intensive short-term and long-term soil conservation works, significant erosion and soil loss would occur from this class of land.

Thus, soil erodibility is only one of several factors to consider in assessing the erosion hazard of a site.

The erosion hazard for water can also be conveniently separated into several phases (see Table 4.1) (see Houghton and Charman 1986; Rosewell *et al.* 2007):

- sheet and rill erosion that is dominated by soil detachment and transport by raindrop impact and overland flow
- gully erosion that is dominated by soil detachment and transport by channelised flow in depressions and minor flow lines
- streambank erosion that is dominated by soil detachment and transport by channelised flow in major flow lines.

These are separated out because the basic processes are different for these phases of water erosion. Different methods of assessment are used to evaluate the erosion hazard for these phases. For example Rosewell (1993) can be used to assess the erosion hazard for sheet and rill erosion as can the land classes in Emery (1986) ([http://www.dlwc.nsw.gov.au/care/soil/soil\\_pubs/pdfs/capability1.pdf](http://www.dlwc.nsw.gov.au/care/soil/soil_pubs/pdfs/capability1.pdf) then same for parts 2, 3, and 4) and Sonter *et al.* (2007). Various computer-based tools at the website for the Cooperative Research Centre for Catchment Hydrology (e.g. SedNet) can be used to assess the potential for gully and streambank erosion (Wilkinson *et al.* 2004; <http://www.toolkit.net.au>).

#### 4.2.2 Erosion hazard for wind

The concept of erosion hazard caused by wind or water is the same (Leys pers. comm.; Geeves *et al.* 2007b). The difference lies in the agent and factor that cause the erosion.

The wind erosion hazard of a parcel of land refers to its susceptibility to wind erosion. The principle factors include:

- *Climate.* The greater the wind frequency and velocity and the lower the rainfall, the higher the wind erosion hazard.

- *Slope and exposure to wind.* Both these factors influence the wind force delivered to a parcel of land. Windward facing slopes and hillcrests have a greater exposure to the wind than level land and leeward facing slopes.
- *Wind fetch.* As wind fetch increases, the rate of erosion increases to maximum then decreases to a quasi-equilibrium. Therefore, if the fetch is small (like between non-eroding grass strips) then the erosion rate will never reach its potential for that wind speed.
- *Upstream wind conditions.* Windbreaks can substantially reduce the mean wind speed to levels below that which would induce erosion. Similarly, a gap in a hill or windbreak will lead to accelerated wind speeds.
- *Soil erodibility.* Erodibility varies with soil texture, aggregate size and aggregate density. While texture is fairly static, soil aggregation is highly variable. The normal aggregate size of clays is such that they are not susceptible to erosion. However, in extended dry spells and after trampling by stock, the aggregate size of clays may be reduced, increasing susceptibility to wind erosion.
- *Land use.* Land use influences vegetation cover levels, crusting and aggregate size distributions.
- *Soil moisture.* Soil moisture above threshold levels can limit wind erosion as moist soils are more resistant to wind erosion.

Wind erosion hazard can be defined into three broad groups (see Table 4.2).

**Table 4.2.** Wind erosion hazard

Rating	Description
Low	The combination of factors that influence wind erosion result in barely perceptible erosion levels.
Moderate	Some factors adversely combine to result in significant short-term erosion. Control of the erosion requires conservation land management practices such as stubble retention and conservative stocking rates.
High	The majority of factors combine to result in major erosion, which occurs repeatedly. Control of the erosion requires high levels of management inputs and specialised conservation land management practices such as windbreaks, permanent pastures and reduced stocking pressure.

## 4.3 Soil erodibility for water erosion

### 4.3.1 Estimating general soil erodibility

Soil erodibility for water erosion reflects the susceptibility of the soil to detachment and transport by water. It is influenced by soil texture and the strength of bonds between soil particles (aggregate stability). Soils with low infiltration rates accelerate erosion because of high runoff rates. A soil with low infiltration and weak bonding between soil particles will be very susceptible to erosion. A tilled soil with a surface crust is an example (Murphy and Flewin 1993).

The soils with the highest erodibility are those with weak bonds between soil particles and an abundance of soil particles that are easily transported by flowing water.

If these properties are combined with low infiltration the soil erodibility is very high. Typical soils with these properties include:

1. Soils high in silt and fine sand and having low organic matter levels
2. Self-mulching clays
3. Dispersible clay soils (usually sodic)

**Table 4.3.** Soil erodibility classes based on soil morphology

Soil classification based on Northcote (1979) and Isbell (1996).

Erodibility	Topsoil	Subsoil
Low <sup>†</sup>	High organic matter (>3%) (soils have a dark colour and feel greasy when textured). High coarse sand.	Cemented layers including iron, manganese and silicon pans such as laterite, silcrete and ortstein. High coarse sand.
Moderate	Moderate organic matter (2–3%). Moderate fine sand and silt, such as hard, pedal red duplex soils. Well-structured clay loams and clays that slake in water to particles less than 2 mm in diameter (Emerson Aggregate Classes 3–6), such as black earths and cracking clays (Ug5.1, Ug5.2 and Ug5.3 soils or Vertosols).	Stable, non-dispersible loams and clay loams (Dr2 soils or Red Chromosols) such as red and yellow massive earths (Gn2.1 and Gn2.2 soils or Yellow Kandosols). Non-dispersible or slightly dispersible clays with particles that slake to finer than 2 mm diameter (Emerson Aggregate Classes 3–6), such as non-sodic, red and yellow soils (Dr, Db and Dy soils or Chromosols).
High	Low (1–2%) to very low (<1%) organic matter, such as soils with bleached A <sub>2</sub> horizons. High to very high silt and fine sand (>65%).	Dispersible clays (Emerson Aggregate Classes 1 and 2) such as sodic, yellow and red soils (Dy3.4, Dr3.4, Dr2.3 soils or Sodosols). Unstable, dispersible clayey sands and sandy clays, such as yellow and grey massive earths formed on sandstone and some granites (Gn2.3, Gn2.8, Gn2.9, Dy5.8 soils or Yellow and Grey Kandosols). Unstable materials high in silt and fine sand, such as unconsolidated sediments and alluvial materials.

Source: Geeves *et al.* (2007b).

<sup>†</sup>Well-structured, non-dispersible clay loams and clays having aggregates that do not slake in water to particles less than 2 mm diameter (Emerson Aggregate Classes 4, 6, 7 and 8) such as red, smooth and rough-ped earths (Gn3, Gn4 soils or Dermosols), some cracking clays (Ug5.1, Ug5.2, Ug5.3 soils or Vertosols), some structured loams (Um6.1 soils, Dermosols) and friable duplex soils (Dr4, Db3 soils or Dermosols).

Caution should be shown in using this assessment of soil erodibility as soil erodibility is only one component of erosion hazard, the others being: rainfall erosivity, slope length and degree, surface cover and land management practice (see Rosewell 1993). Tables 4.3, 4.4 and 4.5 can be used to classify soil erodibility.

**Table 4.4.** Soil erodibility classes based on USLE

USLE, universal soil loss equation.

Rating	K of the USLE t/ha/yr per unit of rainfall erosivity
Very low	0.00–0.01
Low	0.01–0.02
Moderate	0.02–0.04
High	0.04–0.06
Very high	>0.06

Source: Rosewell and Loch (2002).

These erodibilities only relate to erosion at the field or paddock scale, not to gully or streambank erosion.

**Table 4.5.** Estimating USLE K factors from soil texture

USLE, universal soil loss equation.

Soil	Symbol	Suggested K factor
Sand	S	0.015
Clayey sand	CLS	0.025
Loamy sand	LS	0.020
Sandy loam	SL	0.030
Fine sandy loam	FSL	0.035
Sandy clay loam	SCL	0.025
Loam	L	0.040
Loam, fine sandy	Lfs	0.050
Silt loam	SiL	0.055
Clay loam	CL	0.030
Silty clay loam	SiCL	0.040
Fine sandy clay loam	FSCL	0.025
Sandy clay	SC	0.017
Silty clay	SiC	0.025
Light clay	LC	0.025
Light medium clay	LMC	0.018
Medium clay	MC	0.015
Heavy clay	HC	0.012

Source: Rosewell (1993).

The suggested K values are for the mid-points of a texture class. Use average values for soils that lie between classes. Typical erosion rates for NSW soils under different land uses are presented in Edwards and Zierholz (2000).

Sediment export risk levels can be derived using USCS and Emerson dispersion class (see Table 4.6) and can be used to predict soil erodibility in urban areas.

**Table 4.6.** Sediment export factor risk levels derived from USCS classification and Emerson dispersion class

e, extreme; h, high; m, moderate; l, low. (Adapted from Marsh 2002.)

USCS class	Emerson dispersion class						
	1	2	3	4	5	6	7
GW well-graded gravels, little or no fines	l	l	l	l	l	l	l
GP poorly graded gravels, little or no fines	l	l	l	l	l	l	l
GM silty gravels	m	m	m	l	l	l	l
GC clayey gravels	m	m	m	m	l	l	l
SW well-graded sands	l	l	l	l	l	l	l
SP poorly graded sands	l	l	l	l	l	l	l
SM silty sands	h	m	m	m	l	l	l
SC clayey sands	h	h	m	m	m	l	l
ML inorganic silts and very fine sands	e	h	h	m	m	l	l
CL inorganic clays of low plasticity	e	e	h/e	h	h	m	m
OL organic silts and silty clays	e	h	h	m	m	l	l
MH inorganic silts, micaceous fine sands and silts	e	h	h	m	m	l	l
CH inorganic clays of high plasticity	e	e	h/e	h	h	m	m
OH organic clays, medium to high plasticity	e	e	h/e	h	h	m	m
PT peat, highly organic soils	e	h	h	m	m	l	l

### 4.3.2 Regolith erodibility for forestry

Regolith erodibility has been estimated for forest soils in NSW by Murphy *et al.* (1998). This estimate of erodibility is the basis for predicting erosion and potential pollution of stream systems associated with forestry operations. The estimate of erodibility is based on a combination of the coherence between soil particles (detachability) and the potential for sediment delivery to streams (transportability). The regolith materials with the highest erodibility are those with low coherence and high potential for sediment delivery (see Table 4.7).

**Table 4.7.** Conceptual framework of regolith stability class

	Low sediment delivery	High sediment delivery
High coherence	R1 high ferro-magnesium regolith (basalt and dolerite) fine-grained argillaceous soil regolith with high gravel content (siltstones, metasediments) highly organic soil regolith (peats)	R3 fine-grained argillaceous (clay) soil regolith with low/no gravel content fine-grained massive soil regolith
Low coherence	R2 unconsolidated sands medium to coarse-grained feldspathic-quartzose soil regolith (ademillite, quartz sandstone)	R4 unconsolidated deposits of silt and clay unconsolidated fine-grained weathered soil regolith (saprolite)

### 4.3.3 Rainfall erosivity

Rainfall erosivity in the Universal Soil Loss Equation is the ability of the rain to cause erosion. Its derivation is described in Rosewell and Turner (1992) and Rosewell (1993). Its basic units are MJ.mm/(ha.h.yr). The actual distribution of rainfall erosivity in NSW is discussed in detail in Rosewell and Turner (1992). The rainfall erosivity ranges from less than 1000 rainfall erosivity units in the south-west slopes and western part of NSW to more than 6000 along the coast.

As an example of how the rainfall erosivity can be used, taking into account the SOILOSS program (Rosewell 1993), the Kiama Soil Landscape has a general soil erodibility of 0.019 t/ha/yr per unit of rainfall erosivity and the area has an annual average rainfall erosivity of 6000. The estimated soil loss for the first 12 months of urban development ranges from 370 t/ha for topsoil on steeper slopes (20% gradient and 150 m slope length) to 50 t/ha for exposed subsoil on lesser slopes (5% gradient and 150 m slope length) (Hazelton 1992).

Erosion rates for different soil management practices are presented in Edwards and Zierholz (2007).

### 4.3.4 Erosion rates and soil depth

Table 4.8 shows that the amount of soil lost can be expressed in tonnes/ha or as an equivalent depth of soil (mm), based on the relation:

$$\text{Soil lost (t/ha)} = \text{Depth of soil lost (mm)} \times (1 \text{ m}/10^3 \text{ mm}) \times \rho_b \text{ (t/m}^3\text{)} \times 10^4 \text{ m}^2/\text{ha}.$$

**Table 4.8.** Soil loss (t/ha) equivalent to various thicknesses of soil lost (mm)

Bulk density (g/cm <sup>3</sup> or t/m <sup>3</sup> )	Soil mass (t/ha) equivalent to erosion to different depths (mm)				
	1 mm	5 mm	10 mm	50 mm	100 mm
1.2	12	60	120	600	1200
1.4	14	70	140	700	1400
1.6	16	80	160	800	1600

### 4.3.5 Key references

Rosewell and Turner (1992); Rosewell (1993); Edwards and Zierholz (2007); Geeves *et al.* (2007b).

## 4.4 Soil erodibility for wind erosion

Soil erodibility for wind erosion reflects the susceptibility of the soil to detachment and transport by the erosive agent, wind (McTainsh and Leys 1993 and Geeves *et al.* 2007b). For wind erosion, soil texture is a good guide to soil erodibility. Sandy soils (greater than 90% sand by weight), particularly those with fine sand, tend to have high erodibility, sandy loams to clay loams have moderate erodibility, and clays have a low erodibility. The exception to this rule is for highly aggregated clays that can break down into aggregate sizes similar to sand size grains.

### 4.4.1 Soil erodibility ratings for wind

Soil erodibility for wind is more closely linked to aggregate size, specifically 0.85 mm (Geeves *et al.* 2007b) (see Table 4.14). Soil erodibility is not static. It changes through time as the soil aggregation levels change. These changes are influenced by wetting and drying, root binding, soil crusts, organic matter and calcium carbonate content and management.

Sandy soils, especially those composed of fine sand, will often have very few aggregates >0.85 mm and so are usually the most vulnerable to wind erosion. Most clayey soils are aggregated to some extent and usually the soil mass is composed of aggregates more than 0.85 mm. Some clays that are gypsiferous or highly saline can be composed of fine aggregates less than 0.85 mm and susceptible to wind erosion (see Table 4.9).

**Table 4.9.** Wind soil erodibility based on the mass of particles more than 0.85 mm

Wind erodibility rating	Proportion of aggregates >0.85 mm
High	<10% of soil mass
Moderate	10–30% of soil mass
Low	>30% of soil mass

A method for a more detailed assessment of wind erosion using photo standards is presented in Semple *et al.* (1988) (see Table 4.10).



**Table 4.10.** A wind erosion rating scale for use in paddock surveys

Class	Description
1. Intact	Evidence of soil movement is absent; clods, cultivation furrows and surface trash patterns produced by cultivation remain intact.
2. Moderate	Breakdown of clods and smoothing of cultivation ridges is evident. Soil movement from row to row and the loss of trash may also be evident. Gross movement of coarser soil materials from one paddock to the next, or from one part of the paddock to another part, is not evident.
3. Off site	Movement of coarse soil particles from one paddock to the next, or from one part of a paddock to another part, is evident (e.g. dunes, build up of sand along fence lines).

Source: Semple *et al.* (1988).

#### 4.4.2 Wind erosion rates – soil flux and erosion loss

Soil flux ( $Q$ ) is the horizontal soil transport rate expressed in g/m/s., and is the simplest measurement of soil erodibility by wind or wind erosion hazard. Soil erosion loss is expressed as loss of soil in t/ha. This is different to the soil flux, which is the movement of soil material past a line, usually standardised to 1 m.

For soil flux there are three classes used based on two methods of rating:

- (i) Rates based on wind tunnel measurements but corrected for saltation overshoot and adjusted to an equilibrium soil flux (Shao and Raupach 1992; Leys *et al.* 1996) (see Table 4.11).

**Table 4.11.** Ratings of soil flux based on data from a wind tunnel

Rating	Soil flux ( $Q$ ) (g/m/s)
High	>25
Moderate	5–25
Low	<5

Source: Leys and Heinjus (1992); Geeves *et al.* (2007b).

These rates are much higher than natural wind erosion rates because of the constant wind flux.

- (ii) Rates based on field evidence from dust traps in the paddock (see Table 4.12).

**Table 4.12.** Ratings of soil flux based on field evidence

Rating	Soil flux ( $Q$ ) (g/m/s)
High	>1.0
Moderate	0.1–1.0
Low	<0.1

Source: Leys (pers. comm. 1991).

For soil loss the classes of wind erodibility ratings are summarised in Table 4.13.

**Table 4.13.** Relative wind erodibility ratings based on wind tunnel results

Wind erodibility grouping (WEG)	Soil surface texture class	Wind erodibility index (t/ha)
1	very fine sand fine sand coarse sand	659
2	loamy very fine sand loamy fine sand loamy sand loamy coarse sand sapric soil materials	300
3	very fine sandy loam fine sandy loam sandy loam coarse sandy loam	193
4	clay silty clay non-calcareous clay loam silty clay loam with >35% clay	193
4 L	calcareous loam calcareous silt loam calcareous clay loam calcareous silty clay loam	193
5	non-calcareous loam non-calcareous silt with <20% clay sandy clay loam sandy clay hemic organic soils	126
6	non-calcareous loam with >20% clay non-calcareous clay loam with <35% clay	108
7	silt non-calcareous silty clay loam with <35% clay and fibric organic material	85
8	soils not susceptible to wind erosion	0

**Table 4.14.** Wind erodibility classification according to sediment transport rate at a wind speed of 65 km/h. (Geeves *et al.* 2007b)

Erodibility class	Sediment transport rate (g/m/s.)	Dry aggregates >0.85 mm	Clay content (%)
Low	<5	>31	>13%
Moderate	5–25	11–31	6–13%
High	>25	<31	<6%

#### 4.4.3 Key references

Sample *et al.* (1988); McTainsh and Leys (1993); Geeves *et al.* (2007b).



# 5

## Soil chemical properties

### 5.1 Soil acidity

#### 5.1.1 pH

The pH is a measure of soil acidity or alkalinity that gives an indication of the activity of the hydrogen ion ( $H^+$ ) and hydroxyl ion ( $OH^-$ ) in a water solution. Both these ions have a high chemical activity. Their chemical activity is lowest when the solution or soil is close to a neutral pH of 7.0. The pH characterises the chemical environment of the soil and may be used as a guide to suitability of soils for various pasture and crop species. Soil pH is also an indicator of the chemical processes that occur in the soil, and is a guide to likely deficiencies and/or toxicities (Slattery *et al.* 1999). Dragan (1998) also provides guidelines for interpreting soil pH values for environmental evaluation.

#### 5.1.2 Measurement of pH

Soil pH is usually measured in water or in 0.01M  $CaCl_2$  solution at a ratio of one part of soil to five parts of water by weight. Because these two methods can give quite different values, statements of pH measurement must show whether the measurement was obtained in water or 0.01M  $CaCl_2$  solution to be meaningful. The conversion below is a general guide only and is dependent on soil type and conditions.

$$pH \text{ soil/water (1:5)} = pH \text{ } CaCl_2(1:5) + (0.5-1.0)$$

Soil pH can be measured in the field using Raupach Indicator (Raupach and Tucker 1959). This measurement usually corresponds to 1:5 pH in water  $\pm 0.5$  pH units (see Table 5.1). However in practice, variation in the age of Raupach indicator used for field measurements can result in a wider variation to  $\pm 1.0$ . Care should be taken to ensure the indicator used is within its use-by date. Calibrated pH meters are more reliable.

**Table 5.1.** General interpretation of pH measured in water (1:5 soil/water ratio)

\*, test for calcium carbonate ( $\text{CaCO}_3$ ). Iron and zinc may be deficient. \*\*, with increasing acidity exchangeable aluminium increases to toxic levels, cadmium and heavy metals become available and molybdenum becomes increasingly unavailable.

pH	Ratings
>9.0	very strongly alkaline
9.0–8.5	strongly alkaline
8.4–7.9	moderately alkaline*
7.8–7.4	mildly alkaline
7.3–6.6	neutral
6.5–6.1	slightly acid
6.0–5.6	moderately acid
5.5–5.1	strongly acid
5.0–4.5	very strongly acid**

Source: Bruce and Rayment (1982).

Tables 5.2, 5.3 and Figure 5.1 are general guidelines for pasture and crops.

**Table 5.2.** Soil pH and lime in pasture establishment

Molybdenum can be limiting in acid soils because of low availability.

Soil pH (1:5 $\text{H}_2\text{O}$ )	Treatment
Above 6.0	Lime or molybdenum (Mo) usually not required.
5.5–6.0	Lime not usually needed; consider using Mo.
4.5–6.0	Lime pellet legume seed; use Mo.
4.0–4.5	Lime pellet legume seed using lime-super, or sow seed into a band of lime; use Mo.
Below 4	Apply lime to raise soil pH; lime pellet legume seed using lime-super or sow seed into a band of lime; use Mo.

Source: Glendinning (1986).

**Table 5.3.** Critical acidity and aluminium levels for crops and pastures

\*EC (electrical conductivity) 1:5 in dS/m; sub. refers to subterranean.

	Very sensitive plants	Sensitive plants	Tolerant plants	Very tolerant plants
Examples of plants	barrel medic canola lucerne	wheat sensitive phalaris barley	wheat phalaris sub. clover cocksfoot perennial rye	lupins triticale oats serradella
pH ( $\text{CaCl}_2$ ) below which yield declines	4.3–4.7 depending on soil group	4.1–4.5 depending on soil group	4.0–4.3 depending on soil group	4.0–4.2 depending on soil group
Extractable Al in $\text{CaCl}_2$ solution above which yield declines	0.1–0.4 ppm	0.4–0.8 ppm	0.8–1.6 ppm	1.6–2.7 ppm
Exchangeable Al as a percentage of cation exchange capacity	*EC <0.07 (infertile soils low CEC); EC 0.07–0.23 (most fertile soils); EC >0.23 (fertiliser bands, saline soils)			
	9–16	16–21	21–32	32–43
	8–12	8–12	12–21	21–30
	0.5–2	2–6	6–10	10–16

Source: Geeves *et al.* (1990); Fenton *et al.* (1993); Fenton and Helyar (2007).

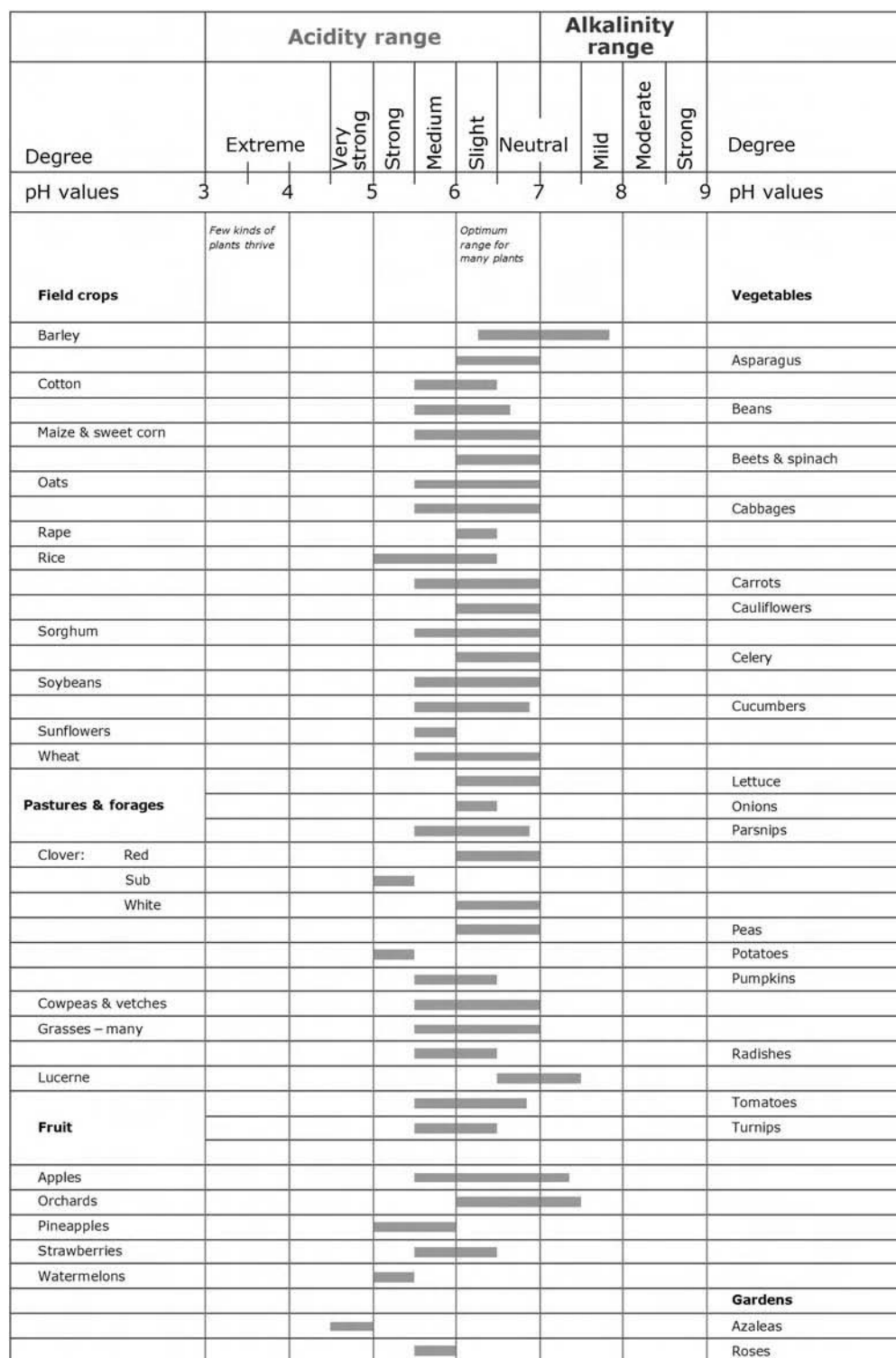


Fig. 5.1. Optimum pH range for a variety of plants.

### 5.1.3 Aluminium toxicity

Test when pH ( $\text{CaCl}_2$ ) is  $<4.7$  (Cregan 1980; Slattery *et al.* 1999) and see Table 5.3.

- Aluminium extracted in 0.01 M  $\text{CaCl}_2$ .

### 5.1.4 Manganese toxicity

Manganese toxicity affects the metabolism of the plant causing chlorosis and necrosis of leaf tissue. Many soils have substantial amounts of manganese. However, it is only when this manganese is released into the soil solution and becomes available that the plants are affected. This release of manganese is favoured by hot, dry conditions that usually happen in summer. This variation in manganese levels during the season makes it difficult to interpret soil tests for manganese. Leaf tissue tests can be used to test for manganese toxicity. For further information see Fenton *et al.* (1993).

Critical levels of manganese that begin to affect yield of sensitive species are as follows:

- Exchangeable Mn  $>0.03$  cmol (+)/kg soil
- Mn extracted by 0.01M  $\text{CaCl}_2$ , 1:5 solution  $>65$  ppm.

Sensitive species include lucerne, medics, white clover, strawberry clover and canola (Fenton *et al.* 1993 and Fenton and Helyar 2007).

### 5.1.5 Expected rates of acidification

The expected rate of acidification will vary between land uses. The rate will be increased by:

- Higher inputs of nitrogen, especially as nitrate ( $\text{NO}_3^-$ ). Nitrate can be added as fertiliser or by including legumes in the pasture or crop rotation as the legumes fix nitrogen from the atmosphere and produce ammonium ion ( $\text{NH}_4^+$ ) that in turn is converted to nitrate in the soil.
- Increased deep drainage that leaches nitrate from the soil. This occurs because the leaching of nitrate also removes cations such as calcium from the soil. The annual rainfall will also affect the rate of leaching.
- High levels of removal of biomass and plant material from the soil as occurs with the production of hay.

Indicative acidification rates for a wide range of pasture and crop rotations are presented in Slattery *et al.* (1999), which indicate the expected acidification rate of the stated land management practices. Whether soils become acidic and to what depth will depend on their initial pH and their buffering capacity (see Table 5.4).

**Table 5.4.** Expected rate of acidification based on the recommended guide for lime requirement

General, minimum application rates of lime required to neutralise the acidification for several agricultural systems in NSW are given. These rates are based on the assumption that sufficient fertiliser is used to maintain a good clover balance in all pastures.

Location and rainfall	Farming system	Lime required to counter acidification (kg/ha/yr)
Plains (<500 mm/yr)	crop or crop/pasture	75
Coastal and tablelands (>500 mm/yr)	perennial pasture	100
Southern tablelands (>500 mm/yr)	perennial pasture	150
	annual pasture	200
	25% crop/75% annual pasture	250
Southern slopes (>500 mm/yr)	perennial pasture	150
	annual pasture	200
	50% crop/50% annual pasture	250
	cropping	300
Irrigation or high rainfall (>1000 mm/yr)	low acidifying N fertiliser (100–300 kg/ha)	450
	high acidifying N fertiliser (>300 kg/ha)	1000
Additions for hay removal (based on kg of lime per tonne of produce)		grass hay: 25 clover hay: 40 lucerne hay: 70

Adapted from Fenton *et al.* (1993), and Fenton and Helyar (2007).

Paddock strips may be used to test for lime response. This involves adding lime to one or several small strips in a paddock. The responses to lime may then be observed.

### 5.1.6 Buffering capacity

Buffering capacity is the ability of a soil to resist changes in pH. It increases with cation exchange capacity and organic matter content. For example, a clayey soil with a high cation exchange capacity will acidify more slowly than a sandy soil. A sandy soil with a low cation exchange capacity can acidify very quickly.

Helyar *et al.* (1990) derived a buffering capacity equation, which can be used for the whole profile. This equation is used to demonstrate the likely range in buffering capacity values as a general guideline.

Another article by Ridley *et al.* (1990) on acidification of undergrazed annual and perennial grass-based pastures shows that permanent perennial pastures acidify more slowly than permanent annual pastures.

### 5.1.7 Influence of soil pH (water) on nutrient availability

The soil pH affects the availability of various nutrients, toxic elements and chemical species to plant roots. The pH is therefore a very good guide to some expected nutrient deficiencies and toxic effects (Brady 1984; McKenzie *et al.* 2004: 16). For detailed diagnostic purposes reference should be made to specific texts such as Peverill *et al.* (1999) and other specialised literature on individual nutrients and toxic chemical species.

As a general guide, the solubility and availability to plants of the following elements is strongly affected by  $\text{pH}_{\text{water}}$ :

Element	pH at which availability is reduced
Phosphorus	pH <5.0 and between 8.5–9.5



Nitrogen	pH <5.0 and >9.0
Potassium	pH <5.0
Sulfur	pH <5.0
Calcium	pH <5.0 and >9.0
Magnesium	pH <5.0 and >9.0
Iron	pH <7.5
Manganese	pH <4.5 and >8.0
Boron	pH <4.5 and between 7.5–8.5
Copper and zinc	pH <4.5 and >8.0
Molybdenum	pH <5.5
Aluminium	pH >5.5

### 5.1.8 Key references

Cregan (1980); Bruce and Rayment (1982); Glendinning (1986); Helyar *et al.* (1990); Ridley *et al.* (1990); Fenton *et al.* (1993); Slattery *et al.* (1999); Fenton and Helyar (2007).

## 5.2 Exchangeable cations

### 5.2.1 Cation exchange capacity (CEC)

Cation exchange capacity is the capacity of the soil to hold and exchange cations. It provides a buffering effect to changes in pH, available nutrients, calcium levels and soil structural changes. As such it is a major controlling agent of stability of soil structure, nutrient availability for plant growth, soil pH, and the soil's reaction to fertilisers and other ameliorants. A low CEC means the soil has a low resistance to changes in soil chemistry that are caused by land use (see Table 5.5).

CEC units are usually expressed as centimoles of positive charge per kg of soil [cmol(+)/kg], which is numerically equivalent to the previously used unit of milli-equivalents per 100 g (me/100 g). CEC is usually estimated by displacing the exchangeable cations (Na, Ca, Mg, K) with another strongly adsorbed cation, and then determining how much of the strongly adsorbed cation is retained by the soil. The strongly adsorbed cation is supplied by reagents such as ammonium chloride, ammonium acetate, silver thiourea, barium chloride and potassium chloride. Details of these methods and their advantages and disadvantages are discussed in Rayment and Higginson (1992) and Rengasamy and Churchman (1999).

**Table 5.5.** Ratings for cation exchange capacity

\*, soils with CEC less than three are often low in fertility and susceptible to soil acidification.

Rating	CEC cmol (+)/kg
Very low	<6*
Low	6–12
Moderate	12–25
High	25–40
Very high	>40

Source: Metson (1961).

### 5.2.2 Exchangeable cations

The five most abundant cations in soils are calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), potassium ( $\text{K}^+$ ), sodium ( $\text{Na}^+$ ) (see Table 5.6) and, in strongly acid soils, aluminium ( $\text{Al}^{3+}$ ). The cations manganese ( $\text{Mn}^{2+}$ ), iron ( $\text{Fe}^{2+}$ ), copper ( $\text{Cu}^{2+}$ ) and zinc ( $\text{Zn}^{2+}$ ) are usually present in amounts that do not contribute significantly to the cation complement. Therefore, it is common practice to measure the concentrations of only the five most abundant cations. These may be summed to give an approximate value of CEC called the Effective CEC. The individual cations may then be expressed as a percentage of the Effective CEC (Abbott 1989).

**Table 5.6.** Levels of exchangeable cations ( $\text{cmol}(+)/\text{kg}$ )

Cation	Very low	Low	Moderate	High	Very high
Na	0–0.1	0.1–0.3	0.3–0.7	0.7–2.0	>2
K	0–0.2	0.2–0.3	0.3–0.7	0.7–2.0	>2
Ca	0–2	2–5	5–10	10–20	>20
Mg	0–0.3	0.3–1.0	1–3	3–8	>8

Source: Metson (1961).

It has been suggested that the proportions of the various cations of the Effective CEC (expressed as a percentage) are more relevant to plant performance than the actual levels (see Table 5.7).

**Table 5.7.** A guide to desirable proportions of CEC of different cations for many plants

Cations	Ranges (% CEC)
Calcium	65–80
Magnesium	10–15
Potassium	1–5
Sodium	0–1
Aluminium	<5

Source: Abbott (1989).

Sandy soils and acid soils that have been strongly leached often have very low levels of exchangeable calcium and magnesium, and plant growth may be limited as a result. Also, exchangeable potassium levels below  $0.2 \text{ cmol}(+)/\text{kg}$  suggest that a plant response to the application of potassium fertiliser is possible, particularly where heavy removal of potassium by harvesting or grazing occurs (Abbott 1989).

Exchangeable Al only becomes significant at pH levels less than 5.5 in water or about 4.7 in  $\text{CaCl}_2$ . The  $\text{Al}^{3+}$  cation can be toxic to roots and is one of the major reasons that soil acidity can affect plant growth (see Section 5.1.3) (Cregan 1980; Fenton and Helyar 2007).

Soils that are high in sodium and magnesium show more dispersion than soils that are high in sodium and calcium (Abbott 1989; Emerson and Bakker 1973) (see Table 5.8).

**Table 5.8.** Ca/Mg ratio

Ca/Mg ratio	Description
<1	Ca deficient
1–4	Ca (low)
4–6	balanced
6–10	Mg (low)
>10	Mg deficient

Source: Eckert (1987).

### 5.2.3 Base saturation

Base saturation (BS) is the percentage of cation exchange capacity that is saturated with potassium, calcium, magnesium and sodium ions.

$$BS = (K+Ca+Mg+Na) \times 100/CEC$$

It provides an indication of how closely nutrient status approaches potential fertility. This may be affected by variable charge of the clay minerals in the soil, and interpretation of results can be difficult (see Rengasamy and Churchman 1999).

The range 60–80% base saturation may be regarded as satisfactory for pastures, with a tolerance value of  $\pm 10\%$  (see Tables 5.9–5.10).

**Table 5.9.** Ratings of base saturation

Range (% BS)	Rating
0–20	very low
20–40	low
40–60	moderate
60–80	high
>80	very high

Source: Metson (1961).

**Table 5.10.** Base saturation as a criterion of leaching

Base saturation figures for the soil profile may be regarded as an indication of intensity of leaching or extent of leaching, in the sense of depletion of the exchangeable 'bases'.

Range (% BS)	Rating
70–100	very weakly leached
50–70	weakly leached
30–50	moderately leached
15–30	strongly leached
0–15	very strongly leached

Source: Metson (1961).

### 5.2.4 Key references

Metson (1961); Eckert (1987); Abbott (1989); Rengasamy and Churchman (1999).

## 5.3 Nitrogen (N) in soil

### 5.3.1 Nitrogen in soil

Nitrogen occurs in the soil in several forms, only some of which are available to plants. Generally nitrogen has to be in a mineralised form (nitrate or ammonium) to be readily available to plants. A discussion of the nitrogen cycle and availability in soils is presented in Strong and Mason (1999). Various pools of nitrogen occur in the soil. The nitrogen in the soil organic matter pool is mineralised to form nitrate ( $\text{NO}_3^-$ ) and ammonia ( $\text{NH}_4^+$ ) that are the forms most available to plants. Nitrate can be readily leached or in water-logging conditions can be subject to denitrification to nitrous oxide ( $\text{N}_2\text{O}$ ) and nitrogen gas ( $\text{N}_2$ ). Nitrous oxide is a significant greenhouse gas that can add to global warming, especially as it is 296 times more effective as a greenhouse gas than carbon dioxide and it has been estimated to contribute up to 6% of the greenhouse gas warming effect (Dalal *et al.* 2003a, 2003b).

Estimating critical values for nitrogen requires local knowledge of soils and climatic conditions. Therefore local advisors should be consulted to obtain recommendations on the addition of nitrogen fertilisers.

### 5.3.2 Total nitrogen

Total nitrogen measures the total amount of nitrogen present in the soil, much of which is held in organic matter and is not immediately available to plants (see Table 5.11). It may be mineralised to available forms. Total nitrogen cannot be used as a measure of the mineralised forms of nitrogen ( $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ), as much of it is held in the organic matter in the soil.

Table 5.11. Ratings for total nitrogen

Rating (% by weight)	Description
<0.05	very low
0.05–0.15	low
0.15–0.25	medium
0.25–0.50	high
>0.5	very high

Source: Bruce and Rayment (1982).

### 5.3.3 Carbon/nitrogen ratio (C/N)

The carbon/nitrogen ratio measures the relative nitrogen content of organic materials. It can be measured for soil carbon or for organic materials. It is usually lower for soil carbon.

It is relevant to the breakdown of organic materials in the soil and is especially applicable in discussing the effects of crop residues on soil nitrogen levels and the rate of breakdown of crop residues. Allison (1973) suggests the interpretation of the C/N ratio of organic material shown in Table 5.12.

**Table 5.12.** Interpretation of C/N ratio of organic materials added to the soil

C/N ratio	Interpretation
<25	Decomposition may proceed at the maximum rate possible under environmental conditions.
>25	Decomposition slows unless nitrogen is added. Nitrogen will be tied up in organisms decomposing the organic material, and will not be available to any crops sown (nitrogen immobilisation occurs).

A figure of 10–12 is normal for an arable soil. Ratios of 15–25 indicate a slowing in the decomposition process, while figures >25 show that the organic matter is ‘raw’ and is unlikely to break down quickly. Where the C/N ratio is <10 it is likely to break down very rapidly (see Table 5.13). Organic matter with a high C/N ratio (>20) also locks up nitrogen as it decomposes, decreasing available nitrogen for the crop (Strong and Mason 1999). The rate of decomposition of organic material is also dependent on the presence of resistant structures and organic compounds in the organic materials. For example, organic materials high in lignin, suberin and polyphenols (many woody materials) are likely to show more resistance to decomposition than would be expected from their C/N ratios. On the other hand, organic materials such as cotton tape made up of readily available carbon compounds, will show a low resistance to decomposition should there be an external source of nitrogen available (Newey 2006).

**Table 5.13.** Ratings for C/N ratio for organic materials added to the soil

Range of C/N ratio	Rating
<10	very low
10–15 e.g. lucerne litter (leaves)	low
15–25 e.g. lucerne roots	medium
25–70 wheat stubble and roots	high
70–100 e.g. <i>Phalaris</i> and <i>Themeda</i> litter and roots	very high
>100 cellulose	extremely high (very nitrogen deficient)
860 cotton tape	approximate end point (essentially having zero nitrogen)

Source: Metson (1961); Newey (2006).

### 5.3.4 Nitrate ( $\text{NO}_3^-$ )

The nitrogen that is readily available to plants is generally measured as nitrate. Nitrate levels can be highly variable in soils. Samples need to be taken at specific times, and transported and stored under carefully controlled conditions (see Holford and Doyle 1992).

The interpretation of nitrate levels in the soil is determined by:

- rainfall and level of stored water at sowing
- time of sampling
- depth over which the sample is taken.

Reliable interpretation of nitrate levels requires localised agronomic experience, but some general recommendations can be made based on information presented in Holford and Doyle (1992) and Strong and Mason (1999).

### 5.3.5 Plant testing

If grain protein is less than 11.5% this could indicate a soil nitrogen deficiency (Verroll and Komoll 1991) (see also Reuter and Robinson 1997). Likely nitrogen response can be seen in Tables 5.14–5.16.

**Table 5.14.** Likely response to nitrogen fertiliser for wheat in southern NSW  
(Sampling depth 0–30 cm.)

Soil nitrate mg/kg	Rating of likely response to fertiliser
>30	adequate, no response
<8	deficient, good chance of response

Source: Holford and Doyle (1992).

**Table 5.15.** Probability of a profitable response to nitrogen fertiliser for cereal cropping in northern NSW

These recommendations are based on experiments conducted in 1985–87. Nitrate was determined on air dried soil samples taken from 0–15 cm depth.

Soil nitrate (mg/kg)	Probability (%)	No. of trials
0–6	100	5
7–15	100	10
16–22	60	5
23–30	50	8
*>30	0	4

Source: Holford and Doyle (1992).

**Table 5.16.** Nitrogen fertiliser requirements for wheat

\*, when the rainfall during fallow is 150–250 mm, or in-crop, 250–350 mm.

Soil nitrate (0–15 cm depth)		Fertiliser requirement (kg urea per ha)	
(mg/kg)	(kg/ha)	Normal rainfall*	Low rainfall
3 or less	6 or less	300	150
4–6	7–12	240	100
7–10	13–20	160	50
11–14	21–28	120	0
15–19	29–38	75	0
20–24	39–48	50	0
25–29	49–58	25	0
30 or more	59 or more	0	0

Source: Holford and Doyle (1992).

For interpretation of plant tissue tests see Reuter and Robinson (1997).

### 5.3.6 Nitrate toxicity

High levels of nitrate in groundwater can become toxic. Excessive use of fertilisers and applications of effluent can cause nitrate levels to become high.

Based on the National Health and Medical Research Council (NHMRC 2004), the following values are applicable to potable water:

- Infants under three months have an upper limit of 50 mg/L.
- Children above three months and adults can safely drink water with up to 100 mg/L.

### 5.3.7 Key references

Metson (1961); Bruce and Rayment (1982); Verroll and Komoll (1991); Holford and Doyle (1992); Strong and Mason (1999); Newey (2006); NHMRC (2004).

## 5.4 Phosphorus (P) in soil

### 5.4.1 Phosphorus in soil

Phosphorus is an essential constituent of numerous substances involved in biochemical reactions including photosynthesis and respiration. It is a major component of adenosine diphosphate (ADP) and adenosine triphosphate (ATP). These are used to supply energy for many biochemical reactions in plants and animals. Phosphorus levels in soil can be used as a guide to indicate whether phosphate fertiliser is required for plant growth. There are various tests used to determine extractable phosphorus depending on the soil and plant species for which the test is being done. Responses to phosphorus based on soil test results can vary widely and consultation with local advisors is recommended.

Phosphorus is in various forms in the soil, only some of which are actually available to plants. Various phosphorus extraction methods are used to simulate the capacity of plants to extract phosphorus from the soil. A discussion of the processes influencing the availability of phosphorus in soils to plants is presented in Moody and Bolland (1999). Recommendations for a range of phosphorus tests based on species are also presented in this reference. A series of tables (see Tables 5.17–5.19) on interpreting P tests are presented because there is considerable local variation in the use and interpretation of these tests.

**Table 5.17.** Extractable phosphorus for wheat; lactate P (0–10 cm)

Phosphorus (mg P/kg soil)	Rating
<5	very low
5–10	low
10–17	moderate
17–25	high
>25	very high

Source: Holford and Cullis (1985).

**Table 5.18.** Extractable phosphorus for pasture; Bray P (0–7.5 cm)

Bray No. 1 P (mg/kg)	Probability of response to applied P
<b>Northern tablelands of NSW</b>	
<12	likely
12–24	possible
>24	unlikely
<b>Central and southern tablelands of NSW</b>	
<8	likely
8–14	possible
>14	unlikely

Source: Abbott (1989).

**Table 5.19.** Soil phosphorus test

Critical values for NSW based on different extracting agents (mg/kg or ppm). These are indicative only and local advice is required for specific on-site fertiliser recommendations.

Soil test	Northern tablelands	Central tablelands	Western slopes	Plains
	moist	moist	dry	dry
Lactate	17	18	13	12
Bray 2	39	46	33	29
Truog	33	30	30	23
Bray No. 1	29	34	18	20
Mehlich	—	58	36	55
Bicarbonate	50	44	27	28

Source: Holford (1990).

Estimating critical values for phosphorus requires local knowledge of soils and climatic conditions. Therefore local advisors should be consulted to obtain recommendations on the addition of phosphorus fertilisers.

#### 5.4.2 Phosphorus requirements based on location and sorption rating of the soil

Phosphorus sorption relates to the capacity of the soil to immobilise phosphorus (see Moody and Bolland 1999). The reactivity (sorption) controls the effectiveness of fertiliser in raising yields and is a measure of the tendency of the soil to bind phosphorus in forms that are poorly available to plants. Two tests are required to predict the rate of phosphorus necessary for plants, the phosphorus level in ppm and the phosphorus sorption of the soil. Two soil tests commonly used to estimate phosphorus in NSW are the lactate test and the Bray No. 1 test. Interpretations for the results of these tests are given in Table 5.20.



**Table 5.20.** Requirement of double superphosphate (17.5% P) (kg/ha)

Based on lactate test (see Section 5.11 for different types of fertilisers). These are indicative only and local advice is required for specific on-site fertiliser recommendations. \*, these occur only in the northern region.

Lactate	Sorption rating #					
Soil test for phosphate (mg/kg)	very low	low	medium	medium-high	high*	very high*
<b>North</b>						
3 or less	40	75	105	145	200	265
4–7	35	65	85	115	155	205
8–10	25	35	55	85	115	155
11–14	15	25	35	65	75	96
15–17	5	10	15	25	35	–
18 or more	0	0	0	0	0	–
<b>Central plains (west of 500 mm isohyet)</b>						
3 or less	35	75	100	125	–	–
4–7	25	65	80	95	–	–
8–10	20	35	60	75	–	–
11–14	15	25	35	45	–	–
15–17	5	10	15	25	–	–
18 or more	0	0	0	0	–	–
<b>Central western slopes</b>						
P soil test result (mg/kg)	Granitic soils		Non-granitic soils			
	very low	low	very low	low	medium	medium-high
<b>Normal rainfall</b>						
3 or less	105	130	40	90	115	150
4–7	80	110	35	75	95	120
8–10	65	85	25	55	75	90
11–14	45	65	15	45	65	70
15–17	30	35	10	25	30	40
18 or more	0	0	0	0	0	0
<b>Low rainfall</b>						
3 or less	75	130	30	65	110	150
4–6	45	110	25	40	85	120
7–8	35	70	15	30	65	90
9–10	20	65	10	15	35	60
11–12	5	15	5	5	15	30
13 or more	0	0	0	0	0	0

Source: Holford (1990).

The quantities in Table 5.20 should be doubled for ordinary superphosphate (9% P) and decreased by 10% for triple superphosphate.

This table gives the quantities in kg/ha of double superphosphate (17.5% P) that should be applied for various categories of phosphate content (based on a soil test) and the phosphate sorption rating. The phosphate sorption rating is a measure of the soil minerals' capacity to lock up soil phosphate in unavailable forms.

### 5.4.3 Phosphorus requirements based on Bray test

#### (a) Wheat

**Table 5.21.** Guidelines for phosphate requirement (kg/ha of P)\* for wheat in central and north-western NSW

Values are based on the Bray No. 1 phosphorus soil test and sorption rating in the table for soils of pH more than 5.0 (CaCl<sub>2</sub>). These are indicative only and local advice is required for specific on-site fertiliser recommendations. \*, fertiliser requirement = P requirement ÷ P content (proportion) of fertiliser (e.g. superphosphate requirement = P requirement ÷ 0.095); \*\*, for the definition of these ratings see Section 5.4.3.

Bray No. 1 P (mg/kg)	Sorption rating**				
	low	medium	medium-high	high	very high
<b>Central west (normal rainfall)</b>					
0–5	10	17	24	36	47
6–10	8	15	21	31	40
11–15	6	12	16	24	–
16–20	4	8	11	–	–
21–25	3	6	8	–	–
26–30	2	3	–	–	–
>30	0	0	–	–	–
<b>Central west (dry conditions)</b>					
0–5	10	17	24	36	47
6–10	8	15	21	30	40
11–15	6	9	14	20	–
16–20	2	5	7	–	–
>20	0	0	0	–	–
<b>North-west (normal rainfall)</b>					
0–5	9	15	21	32	42
6–10	8	13	18	27	35
11–15	6	9	14	22	–
16–20	3	6	8	–	–
21–25	2	3	–	–	–
26–30	1	1	–	–	–
>30	0	0	–	–	–

Source: Abbott (1985).

### (b) Pastures

For pastures there is often little choice in the rate of phosphate fertiliser that can be top dressed onto pastures because of the costs of application. Generally soils can be considered as either responsive or not responsive. Usually there is not the scope to apply different rates of fertiliser as there is for cropping.

It should be emphasised that these ratings apply to dryland pasture soils having a pH ( $\text{CaCl}_2$ )  $\geq 5.0$ .

Where pastures are irrigated, the soil P level at which a response becomes unlikely will be higher than 12 mg/kg.

The situation applying to soils of pH ( $\text{CaCl}_2$ )  $< 5$  (i.e. problem acid soils) (see Table 5.23) is at present not well enough defined for the central and north-western wheat areas or for pastures to allow interpretation of soil phosphorus levels with confidence. Available evidence suggests that the soil phosphorus levels at which a response becomes unlikely will be higher than those for soils with pH ( $\text{CaCl}_2$ )  $> 5$  (see Table 5.22).

**Table 5.22.** Suitability of soils for pasture growth where soils have pH ( $\text{CaCl}_2$ )  $> 5.0$

These are indicative only and local advice is required for specific on-site fertiliser recommendations.

Response to applied P	Bray No. 1 P test (mg/kg)
Likely	$< 8$
Possible	8–12
Unlikely	$> 12$

**Table 5.23.** A guide to soil test values and phosphorus status for pastures where soil pH ( $\text{CaCl}_2$ )  $< 5.0$

These are indicative only and local advice is required for specific on-site fertiliser recommendations. \*, adequate soil test value. This is the level at which phosphorus is adequate for healthy growth. If the soil test exceeds this level there is no need for phosphorus fertiliser in that year. If it exceeds this level by a large amount, phosphorus application may be suspended for a longer time, but don't overlook the need for sulfur during this period.

Soil type	Phosphorus status	Phosphorus levels		
		Olsen P mg/kg	Bray-IP mg/kg	Colwell P mg/kg
Sandy loams	low	0–7	0–8	0–14
	medium	7–15	8–15	14–20
	high	$> 15^*$	$> 15^*$	$> 20^*$
Loams	low	0–8	0–10	0–16
	medium	8–18	10–18	16–30
	high	$> 18^*$	$> 18^*$	$> 30^*$
Clay loams	low	0–9	0–10	0–18
	medium	9–24	10–20	18–40
	high	$> 24^*$	$> 20^*$	$> 40^*$
Heavy clay soil	low	0–13	0–10	0–30
	medium	13–30	10–20	30–80
	high	$> 30^*$	$> 20^*$	$> 80^*$

Source: Clements and McGowen (1994).

### 5.4.4 Phosphate sorption

The behaviour of labile inorganic phosphorus in soils is dominated by sorption and desorption processes. The amount of P that a soil will remove from solution (be absorbed) over a standard period of time is related to phosphate buffering capacity. This is a soil property that controls the availability of native soil phosphorus and the effectiveness of fertiliser phosphorus (see Table 5.24).

**Table 5.24.** Phosphate sorptivity ratings for some soils of New South Wales

Parent rock	Soil description	Area	Rating
Granite	sandy sandy	general old rainforest	very low–low very high
Slate and shale	silty loams (bleached)	coast and tablelands	low-medium
	clay loams (A <sub>2</sub> horizon)	coast and tablelands	low-medium
Basalt	krasnozems pH (CaCl <sub>2</sub> ) <5.0	coast and tablelands	high
	red earths, red clays and black earths	slopes and plains	low-medium
	earth (red and yellow)	old rainforest	very high
Basalt	black earths	plains	low-medium
	chocolate soils	tablelands	medium-high
	krasnozems	coast	high
	krasnozems	old rainforest	very high

Source: Abbott (1989).

**Table 5.25.** Phosphorus sorption of a range of Australian soils equilibrated for 24 hours with a solution of P concentration of 0.2 mg/L

Soil	P sorbed (mg/kg)	
	topsoil	subsoil
Krasnozems	133–240	445–965
Xanthozems	55–135	120–290
Euchrozems	25–80	360–250
Red earths	10–100	60–485
Yellow earths	10–70	90–165
Red podsollic	25–155	110–153
Solodic	18	Not done

Adapted from Probert (1994).

The values in Table 5.25 are critical for effluent disposal, as they relate to the capacity of soils to store phosphorus. The total storage capacity can be estimated by combining the phosphorus sorption rating and the bulk density ( $\text{kg/m}^3$ ) to give the storage capacity in kilograms of phosphorus per hectare, per metre of soil depth. Assuming a bulk density of  $1500 \text{ kg/m}^3$ , the storage capacity of the topsoil ranges from 1500 to 3600 kg of phosphorus per hectare, per metre depth of soil. For the same bulk density the storage capacity of the subsoil is 900–14 400 kg of phosphorus per hectare, per metre depth of soil. (Gardner *et al.* 1993).

Phosphorus sorption can be determined by equilibrating the soil with a solution containing phosphorus and calculating a sorption index. This soil test is described in Abbott *et al.* (1993).

### 5.4.5 Key references

Holford and Cullis (1985); Abbott (1989); Holford (1990); Abbott *et al.* (1993); Clements and McGowen (1994); Probert (1994); Moody and Bolland (1999).

## 5.5 Potassium (K) in soil

### 5.5.1 Non-exchangeable available potassium

Plant requirements for potassium (K) are supplied from two soil sources: exchangeable K that is immediately available, and non-exchangeable available potassium (NEAP), which is more slowly available. NEAP is not a useful source of K where the rate of K withdrawal by plants is high and sustained. However, the NEAP pool may supply an appreciable portion of the K taken up in other situations such as for pasture production (see Table 5.26). For a general discussion on deficiencies of potassium in Australian soils see Gourley (1999).

**Table 5.26.** Availability of potassium to plants for different NEAP levels in the topsoil (0–15 cm)

NEAP level in topsoil [cmol(+)/kg]	Approximate amount of available potassium in one season (kg/ha)
<0.5	<44
0.5–1.0	44–88
1.0–2.0	88–132
2.0–4.0	>132

Source: Abbott (1989).

Critical values for K that begin to limit plant growth are around 0.2–0.5 cmol(+)/kg or 80–200 mg/kg (Gourley 1999).

Note that the units for exchangeable or extractable K include both cmol(+)/kg and mg/kg.

To convert the units:

$$\text{mg/kg of exchangeable or extractable K} = 391 \times \text{cmol(+)/kg}$$

(The atomic weight of K is 391 mg per cmol.)

### 5.5.2 Key references

Abbott (1989); Gourley (1999).

## 5.6 Nutrient levels in plants

Testing of plant materials is often used to assess soil nutrient levels. This is especially the case in horticulture. These plant tests can be used to identify nutrient deficiencies and toxicities. A summary of the interpretation of tests for nutrient levels in plants is given in Reuter and Robinson (1997).

## 5.7 Organic matter content of soils

### 5.7.1 Organic matter

Organic matter is the material in soil that is directly derived from plants and animals, and it supports most important microfauna and microflora in the soil. Through its breakdown and interaction with other soil constituents, it is largely responsible for much of the physical and chemical fertility of a soil (Allison 1973; Charman and Roper 2007).

Soil organic matter is a term that is usually used in the broadest sense to describe a wide range of organic components in the soil including living and non-living organic materials. The non-living organic matter can be broken down into dissolved organic matter, particulate organic matter, humus and inert organic matter (charcoal and charred plant materials). A detailed discussion of organic matter in Australian soils is given in Baldock and Skjemstad (1999), who also give a range of critical values for soil carbon.

Organic matter and organic carbon are usually expressed as a percentage of the soil by weight. When results are presented and interpreted, care should be taken to note whether organic matter or organic carbon levels are indicated.

Organic matter is calculated from the levels of organic carbon in the soil by multiplying by 1.72. This factor is based on the assumption that the organic matter in the soil has a constant carbon composition of approximately 57%. However, Nelson and Sommers (1996) have pointed out that the actual conversion factors of organic carbon to organic matter vary from 1.72–2.00, and they recommend that only organic carbon values be reported.

The method of determining soil carbon can influence the results. A LECO (Laboratory Equipment Corporation) furnace is often used to determine soil carbon by combustion and has tended to replace the older, more labour intensive Walkley-Black method, which uses chemical oxidation. Tests have shown these are generally equivalent, or can be converted, provided the exact methodology for the Walkley-Black method has been recorded (Skjemstad *et al.* 2000).

The general ranking of soil organic matter levels (see Table 5.27) has been based on soils that are light-textured (sand loams, loams) and weakly structured. These soils broadly coincide with hard-setting soils.

Note that the values in Table 5.28 relate to the effect of soil carbon on soil condition. Whether values are high or low for a particular area will depend on the climate, including rainfall and temperature. Drier, hotter areas will generally have lower soil carbon values than wetter colder areas. Therefore, an evaluation of whether soil carbon values are high or low for an area will need to take account of the potential for an area to build up soil carbon based on potential biomass production and the potential for organic matter decomposition, which is primarily dependent on rainfall, evaporation and temperature.

**Table 5.27.** The relationship of soil organic matter to soil physical properties

Level of organic matter % (g/100 g)	Level of organic carbon % (g/100 g)	Rating	Interpretation
<0.70	<0.40	extremely low	Subsoils or severely eroded, degraded surface soils.
0.70–1.00	0.40–0.60	very low	Very poor structural condition, very low structural stability.
1.00–1.70	0.60–1.00	low	Poor to moderate structural condition, low to moderate structural stability.
1.70–3.00	1.00–1.80	moderate	Average structural condition, average structural stability.
3.00–5.15	1.80–3.00	high	Good structural condition, high structural stability.
>5.15	>3.00	very high	Good structural condition, high structural stability and soils probably water repellent.

Source: Adapted from Emerson (1991); Charman and Roper (2000).

**Table 5.28.** Proposed rating levels for soil carbon to assess soil health or soil condition

\*, will depend on texture, soil sodicity and presence of free iron.

Level of organic matter (%) (g/100 g)	Level of organic carbon (%) (g/100 g)	Rating	Band	Interpretation*
<0.70	<0.40	extremely low	1	Subsoils or severely eroded, highly degraded surface soils.
0.70–1.00	0.40–0.59	very low	2	Very poor structural condition, very low structural stability.
1.01–1.36	0.60–0.79	low L1	3	Poor to moderate structural condition, low to moderate structural stability.
1.38–1.71	0.80–0.99	low L2	4	
1.72–2.14	1.00–1.19	moderate M1	5	The following improve with increasing soil carbon levels: structural stability, pH buffering capacity, soil nutrient levels (especially nitrogen), water holding capacity.
2.15–2.57	1.20–1.39	moderate M2	6	
2.58–3.09	1.40–1.59	moderate M3	7	
3.10–3.43	1.60–1.79	high H1	8	Good structural condition, high structural stability, pH buffering capacity, soil nutrient levels (especially nitrogen), water holding capacity.
3.44–4.29	1.80–1.99	high H2	9	
4.30–5.15	2.00–2.19	very high VH1	10	Soils with very good soil structure and high buffering capacity with sufficient organic matter to decrease bulk density and improve water holding capacity.
	2.20–2.39	very high VH2	11	
	2.40–2.59	very high VH3	12	
	2.60–2.99	very high VH4	13	
5.16–15.00	3.00–8.70	extremely high	14	Soils obviously have high levels of organic matter (dark coloured, greasy to touch and large amount of organic material in the soil). Usually associated with undisturbed woodlands and forested areas.
>15.00	>8.70	organic soil material	15	Highly organic soil including peat.

### 5.7.2 Estimating carbon densities for greenhouse sinks

Soil carbon is a terrestrial carbon sink, and the amount of carbon stored in the soil is estimated as t/ha. This requires the conversion of carbon, expressed as a percentage of soil weight, to a weight per unit volume. The soil bulk density as described in Section 2.4.1, is required to make this conversion.

The following formula is used to perform the conversion:

$$\text{Carbon density (t/ha) per soil layer} = \text{carbon \%} \times \text{bulk density (t/m}^3\text{)} \times \text{layer depth (m)} \times 10\,000 \text{ (m}^2\text{/ha)}.$$

While this simple formula is generally valid, account needs to be taken of the variation in depth of soil carbon percentage and bulk density, and these values should be summed over the whole soil profile.

For the Kyoto Agreement on the control of carbon emissions, soil carbon density to 30 cm was chosen as the international standard.

A comprehensive description of the methodology for determining soil carbon densities for greenhouse accounting is given in McKenzie *et al.* (2000) and Murphy *et al.* (2003).

Further discussion of soil carbon densities in relation to carbon accounting can be found at the Australian Greenhouse Office website.

Estimates of soil carbon density range from less than 10 to more than 250 t/ha to 30 cm depth. The lower values are in the arid areas and the higher levels in the forested areas with high rainfall or alpine areas with very low temperatures. In the cropping areas on the slopes of NSW values tend to range from 20–50 t/ha to 30 cm depending on rainfall, soil type and land management history.

For more detailed information on soil carbon densities for different climatic zones and soil types see: <http://www.greenhouse.gov.au/ncas/reports/tech12.html> and other associated reports in Technical Series 3, 4 and 5.

### 5.7.3 Key references

Emerson (1991); Baldock and Skjemstad (1999); Charman and Roper (2007); McKenzie *et al.* (2000); Murphy *et al.* (2003).

## 5.8 Nutrients removed in farm products

Large quantities of soil nutrients are removed in agricultural produce. This has significant implications for maintaining the long-term nutrient balance in soils. Burning stubble increases the rate of removal of nutrients. Nitrogen, sulfur and carbon are lost to the atmosphere. Other nutrients such as phosphorus, potassium and the trace elements remain in the ash but can be lost through wind or water erosion. Removal of ash by erosion can increase the level of nutrients in waterways. Tables 5.29–5.31 summarise some of the major losses of soil nutrients in agricultural produce.

Note that canola grain has very high levels of sulfur, approximately five times that in wheat (see Table 5.31).



**Table 5.29.** Nutrients removed by wheat (1976 crop in southern NSW)

Nutrient	Weight of nutrient removed per tonne of grain harvested (kg/t)
Nitrogen	19.5
Phosphorus	3.1
Sulfur	1.5
Potassium	4.3
Magnesium	1.1
Calcium	0.3
Iron	0.04
Manganese	0.05
Zinc	0.02
Copper	0.005
Molybdenum	0.0003

Source: Schulz and French (1976); Lipsett and Dann (1983).

**Table 5.30.** Nutrients removed by various forms of production

	N (kg)	P (kg)	K (kg)	S (kg)	Ca (kg)
One fat lamb	2.3	0.2	0.1	0.2	0.4
One wool fleece	0.7	trace	0.1	trace	trace
1000 litres milk	6.0	1.0	1.4	0.6	1.2
One tonne legume hay	30.0	3.0	25.0	2.0	9.0
One tonne cereal hay	20.0	2.0	18.0	1.4	0.6

Source: Hyland (1995).

**Table 5.31.** Nutrients removed by one tonne of various crops

n/a, not available.

Crop type	N (kg)	P (kg)	K (kg)	S (kg)	Ca (kg)	Mg (kg)	Cu (g)	Zn (g)	Mn (g)
<b>Cereals</b>									
Wheat	23	3.0	4	1.5	0.4	1.2	5	20	40
Barley	23	2.7	5	1.5	0.3	1.1	3	14	11
Oats	17	3.0	5	1.6	0.5	1.1	3	17	40
<b>Grain legumes</b>									
Chickpeas (Desi)	33	3.2	9	2.0	1.6	1.4	7	34	34
Chickpeas (Kabuli)	36	3.4	9	2.0	1.0	1.2	8	33	22
Faba beans	41	4.0	10	1.5	1.3	1.2	10	28	30
Lentils	40	3.9	8	1.8	0.7	0.9	7	28	14
Lupins (sweet)	53	3.0	8	2.3	2.2	1.6	5	35	18
Lupins (white)	60	3.6	10	2.4	2.0	1.4	5	30	60
Peas (field)	38	3.4	9	1.8	0.9	1.3	5	35	14
Mung beans	45	5.1	11	n/a	1.1	1.6	n/a	n/a	n/a
Soy beans	70	4.8	17	n/a	n/a	n/a	n/a	n/a	n/a
<b>Oilseeds</b>									
Canola	41	7.0	9	10.0	4.0	3.8	4	40	40
Linola	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Safflower	25	4.3	9	4.0	2.0	n/a	14	26	13
<b>Pastures</b>									
Lucerne hay	33	3.3	28	2.4	11.0	2.1	6	21	56
Lucerne seed	60	2.9	n/a	n/a	10.0	n/a	n/a	n/a	n/a
Medic hay	30	3.0	25	2.0	9.0	n/a	8	20	15
Medic seed	64	8.4	12	5.0	2.0	n/a	7	23	13

Source: Hyland (1995).

### 5.8.1 Key references

Schulz and French (1976); Lipsett and Dann (1983); Hyland (1995).

## 5.9 Salinity

Soil salinity refers to the accumulation of water soluble salts – mainly of sodium, but also of potassium, calcium and magnesium – which may be chlorides, sulfates or carbonates. These can severely affect plant growth and land use, and increase soil erosion.

Salinity levels are usually determined by measuring the electrical conductivity of soil/water suspensions. Traditionally, the electrical conductivity of saturated extracts was used (EC<sub>e</sub>) but these values are time-consuming and difficult to determine. Electrical conductivity is commonly determined more rapidly and easily on a 1:5 soil/water suspension (EC 1:5). These are converted to EC<sub>e</sub> values based on the estimated water-holding capacities of the soil based on the texture of the soil. Multiplier factors are used for converting EC 1:5 (dS/m) to an appropriate value of EC<sub>e</sub> (dS/m) (see Table 5.33). In soil science the common units for electrical conductivity are deciSiemen per metre (dS/m), but a wide range of units is used in reports and discussions.

DeciSiemen per metre (dS/m) is the standard unit of electrical conductivity for soil suspensions and extracts. It is numerically equivalent to milliSiemen per centimetre (mS/cm) and millimho per centimetre (mmho/cm). One dS/m equals 1000 microSiemen per centimetre ( $\mu\text{S/cm}$  or EC units). (For further units see Taylor 1991 and Table 5.39.) The conductivity of a water solution is directly related to the amount of salt dissolved in the solution, although the relationship varies slightly with the cations and anions present in the solution (Richards 1954).

### 5.9.1 Interpretation of electrical conductivity from a saturated extract (ECe)

Conventionally, saline soils are defined as those having an ECe value  $>4$  dS/m (see Table 5.32).

**Table 5.32.** Salinity ratings for soil based on ECe.

Rating	ECe dS/m	Effect on plants
Non-saline	$<2$	salinity effects are mostly negligible
Slightly saline	2–4	yields of sensitive crops are affected
Moderately saline	4–8	yields of many crops are affected
Highly saline	8–16	only tolerant crops yield satisfactorily
Extremely saline	$>16$	only very tolerant crops yield satisfactorily

Adapted from Richards (1954).

### 5.9.2 Conversion of EC 1:5 to ECe

There is a lot of information about the interpretation of ECe in relation to plant growth. Therefore, it is useful to convert EC (1:5) to ECe.

$$\text{ECe (dS/m)} = \text{EC1:5 (dS/m)} \times \text{multiplier factor}$$

The multiplier factor depends on the moisture holding properties of the soil for which soil texture can be used to give an approximation (see Table 5.33). Therefore EC1:5 values are usually converted to ECe using a conversion factor based on soil texture. It is essential therefore that all EC1:5 results should be accompanied by an assessment of texture. For a method to determine soil texture see: [http://www.dlwc.nsw.gov.au/care/soil/soil\\_pubs/pdfs/soiltexture.pdf](http://www.dlwc.nsw.gov.au/care/soil/soil_pubs/pdfs/soiltexture.pdf).

**Table 5.33.** Multiplier factors for converting EC1:5 (dS/m) to an approximate value of ECe (dS/m)

\*, based on the equation 4 from Slavich and Petterson (1993).  $\text{ECe} = f \text{ EC1:5}$ , where  $f = 2.46 + 3.03/\theta_{\text{SP}}$ , and  $\theta_{\text{SP}}$  is the saturation water content. The  $\theta_{\text{SP}}$  for peat is assumed to be 1.25 based on a bulk density of  $0.8 \text{ t/m}^3$  for a peat soil.

Soil texture	Multiplier factor
Sand, loamy sand, clayey sand	23
Sandy loam, fine sandy loam, light sandy clay loam	14
Loam, fine sandy loam, silty loam, sandy clay loam	9.5
Clay loam, silty clay loam, fine sandy clay loam, sandy clay, silty clay, light clay	8.6
Light medium clay	8.6
Medium clay	7.5
Heavy clay	5.8
Peat*	4.9

Source: Slavich and Petterson (1993).

These simple conversion factors are not always ideal (see Shaw 1999), but generally enable an assessment of the salinity status of a soil. These relationships are largely based on chloride salts, so where large quantities of sulfate and carbonate salts are present, some error may occur using these conversion factors (Shaw 1999). The sparingly soluble salts such as gypsum and some carbonates and silicates may become more soluble with the greater dilution in a 1:5 soil/water extract.

### 5.9.3 Further conversions

Total soluble salts (TSS) was a popular term for expressing soil salinity, and it is still used by a few laboratories. Its units are mg/kg (ppm) or g/100 g (%). The conductivity of a water solution is directly related to the amount of salt present in solution, although the relationship varies slightly depending on the types or species of cations and anions present (Richards 1954). Generally the conductivity is slightly less for multi-charged and larger ions than for smaller, single-charged ions at the same concentrations. The conversion is also influenced by the atomic weight of the cations and ions present in the salt solution. Thus these conversions will vary depending on the type of salts present. These conversions are based on a salt dominated by sodium chloride.

TSS is related approximately to EC1:5 by the formulae:

$$\begin{aligned} \text{TSS (mg/kg)} &= 640 \times \text{EC1:5 (dS/m)} \\ &\text{and} \\ \text{TSS (g/100 g)} &= 0.064 \times \text{EC1:5 (dS/m)} \end{aligned}$$

For a discussion of units see Taylor (1991).

**Table 5.34.** Typical values of EC in water

Electrical conductivity (dS/m)	Example
0.02	rainwater
0.03	normal surface soil (1:5 soil/water extract)
0.06–0.09	river water (these values can be considerably higher in streams affected by salinity)
0.15	1:5 soil/water extract one year after adding 5 t/ha of lime ( $\text{CaCO}_3$ ) (this value is typical, but may vary)
0.25	1:5 soil/water extract one year after adding 2.5 t/ha of gypsum ( $\text{CaSO}_4$ ) (this value is typical, but may vary)
0.35	saturated solution of lime ( $\text{CaCO}_3$ ) with high $\text{CO}_2$ levels (as in a surface soil with rapid root growth)
1.00	poor quality bore water
1.60	common value for saline soil (1:5 soil/water extract)
2.20	saturated solution of gypsum ( $\text{CaSO}_4$ )
2.40	very poor quality bore water, 1:5 soil/water extract for saline soil
8.00	1:5 soil/water extract for highly saline soil
46.60	seawater
>100.00	saturated solution of sodium chloride ( $\text{NaCl}$ ), common salt (various sources)
550.00	Dead Sea water

**Table 5.35.** Classification of saline waters (Rhoades *et al.* 1992)

Water class	Type of water	(dS/m)	(mS/cm)	( $\mu$ S/cm)	(EC units)	(mmho/cm)	Total dissolved solids (TDS) (mg/L) (assuming NaCl is major salt)	Total dissolved solids (ppm) (assuming NaCl is major salt)
Non-saline	drinking and irrigation water	<0.7	<0.7	700	700	<0.7	448	448
Slightly saline	irrigation water	0.7–2.0	0.7–2.0	700–2000	700–2000	0.7–2.0	448–1280	448–1280
Moderately saline	primary drainage water and groundwater	2.0–10.0	2.0–10.0	2000–10 000	2000–10 000	2.0–10.0	1280–6400	1280–6400
Highly saline	secondary drainage water and groundwater	10–25	10–25	10 000–25 000	10 000–25 000	10–25	6400–16 000	6400–16 000
Very highly saline	very saline groundwater	25–45	25–45	25 000–45 000	25 000–45 000	25–45	16 000–28 800	16 000–28 800
Brine	seawater	>45	>45	>45 000	>45 000	>45	>28 800	>28 800

**Table 5.36.** Summary of salinity ratings and levels in water (Ayers and Westcott 1994)

Water	Salinity rating	(dS/m)	(mS/cm)	(µS/cm)	(EC units)	(mmho/cm)	Total dissolved solids (TDS) (mg/L)	Total dissolved solids (ppm) (mg/L)
Limitation to use as irrigation water	none	<0.7	<0.7	<700	<700	<0.7	<448	<448
	slight to moderate	0.7–3.0	0.7–3.0	700–3000	700–3000	0.7–3.0	448–1920	448–1920
	severe	>3.0	>3.0	>3000	>3000	>3.0	>1920	>1920
Interaction between SAR and ECwater for irrigation use	SARwater	Levels of ECwater (dS/m) required to prevent surface sealing and dispersion on susceptible soils (see sodic soils)						
		no limitation			slight to moderate limitation		severe limitation	
	0–3	>0.7			0.7–0.2		<0.2	
	3–6	>1.2			1.2–0.3		<0.3	
	6–12	>1.9			1.9–0.5		<?0.5	
	12–20	>2.9			2.9–1.3		<1.3	
	20–40	>5.0			5.0–2.9		<2.3	
	Limitations to irrigation associated with specific ions (mequiv/L)	none			slight to moderate		severe	
		sodium (Na <sup>+</sup> ):						
		surface			<3		3–9	
		spray			<3		>3	
		chloride (Cl <sup>–</sup> ):						
		surface			<4		4–10	
		spray			<3		>3	
		bicarbonate (HCO <sub>3</sub> <sup>–</sup> ):						
		overhead			<1.5		1.5–8.5	
							>8.5	

**Table 5.37.** Soil salinity ratings with electrical conductivity measured using soil/water ratio of 1:5 for different soil texture (Shaw 1999)

Soil salinity rating	Electrical conductivity ratings (1:5, dS/m) for a range of soil clay contents				Plant response
	10–20% clay	20–40% clay	40–60% clay	60–80% clay	
Very low	<0.07	<0.09	<0.12	<0.15	no effect
Low	0.07–0.15	0.09–0.19	0.12–0.24	0.15–0.30	moderately sensitive crops affected
Medium	0.15–0.34	0.19–0.45	0.24–0.56	0.30–0.70	moderately tolerant crops affected
High	0.34–0.63	0.45–0.76	0.56–0.96	0.70–1.18	tolerant crops affected
Very high	0.63–0.93	0.76–1.21	0.96–0.53	1.18–1.87	very tolerant crops affected
Extreme	>0.93	>1.21	>1.53	>1.87	generally too saline for crop growth

### 5.9.4 Interpretation of test values for salinity

Evaluating the effect of salinity on crop growth can be complex and often requires some consideration of the depth at which the soil layer occurs. Shallow saline soil layers have a larger impact on plant growth than saline soil layers at depth. The interpretation of salinity for crop growth is discussed in detail by Shaw (1999), who also gives a comprehensive list of critical salinity values for a further range of plants. See Table 5.38 for the salt tolerance of some agricultural crops.

**Table 5.38.** Salt tolerance of some agricultural cropsBased on EC of saturated extract, generally labelled as EC<sub>e</sub>; sub, subterranean.

	Sensitive (EC <sub>e</sub> 0–1.9 dS/m)	Maximum EC <sub>e</sub> values for no yield reduction	Moderately tolerant (EC <sub>e</sub> 2.0–3.9 dS/m)	Maximum EC <sub>e</sub> values for no yield reduction	Tolerant (EC <sub>e</sub> >3.9 dS/m)	Maximum EC <sub>e</sub> values for no yield reduction
Field crops	beans (field)	1.0	peanut	3.2	barley	8.0
	broad bean	1.6	rice	3.0	cotton	7.7
	cowpea	1.3			safflower	5.3
	flax	1.7			sorghum	4.0
	maize	1.7			soybean	5.0
	sugar cane	1.7			sugarbeet	7.0
Forage crops					wheat	6.0
	bent grass	1.7	crested wheat	3.5	barley (hay)	6.0
	berseem clover	1.5	grass	2.0	bermuda	6.9
	orchard grass	1.5	lucerne	2.8	grass	
	red clover	1.5	sudan grass	2.3	perennial	5.6
	strawberry clover	1.5	trefoil, big	3.0	ryegrass	
	sub. clover	1.5	vetch		phalaris	4.6
	white clover	1.5			trefoil,	5.0
Vegetable crops					birdsfoot	
	beans	1.0	broad beans	2.3	wheat grass	7.5
	cabbage	1.8	broccoli	2.8	beets	4.0
	cauliflower	1.0	cantaloupe	2.2		
	celery	1.8	cucumber	2.5		
	lettuce	1.0	spinach	2.0		
	onion	1.3	tomato	2.5		
	peas	1.2	watermelon	2.0		
Fruit crops	potato	1.7				
	apple	1.7	fig	2.7	date palm	4.0
	apricot	1.7	grape	2.7		
	avocado	1.3	olive	2.7		
	banana	1.2	pomegranate	2.7		
	grape	1.5				
	grapefruit	1.8				
	lemon	1.7				
	orange	1.7				
	peach	1.7				
	pear	1.7				
	plum	1.5				
	strawberry	1.0				

Main source: Ayers (1977).

### 5.9.5 Salt tolerant pasture recommendations – southern and central New South Wales

Tables 5.39–5.41 list pasture sowing recommendations for three salinity classes. Soil salinity is described as electrical conductivity of the saturated paste extract (EC<sub>e</sub>). The units are decisiemens per metre (dS/m).

The method for choosing the salinity class to which a salt affected area belongs is described in detail by Francis and Marcar (1993).



**Table 5.39.** Pasture sowing recommendations for Class 1 sites (slightly saline), 2–4 dS/m ECe

Appearance: some salt tolerant species (e.g. sea barley grass) but no bare patches.

Species	Sowing rate (kg/ha)
Australian phalaris	2
Tall wheat grass	4–6
Victorian or Kangaroo Valley perennial ryegrass	2
Demeter fescue	4
Palestine strawberry clover	1
Trikala or Gosse subterranean clover	2
Paradana Balansa clover	1
<i>Total</i>	16–18

**Fertiliser**

Use a nitrogen and phosphorus mixture with sulfur present, e.g. Starter 15 at 125 kg/ha.

**Table 5.40.** Pasture sowing recommendations for Class 2 sites (moderately saline), 4–8 dS/m ECe

Appearance: small bare patches.

Species	Sowing rate (kg/ha)
Australian phalaris	2
Tall wheat grass	4–6
Demeter or Triumph fescue	4
Puccinellia	2–4
Victorian or Kangaroo Valley perennial ryegrass	1–2
Palestine strawberry clover	2
Paradana Balansa clover	1
<i>Total</i>	16–21

These recommendations are more suited to areas with annual average rainfall above 700 mm. However, if the site remains wet during early summer, and if the stand is not heavily grazed, persistence in drier areas should be acceptable.

**Fertiliser**

Use a nitrogen and phosphorus mixture with sulfur present, e.g. Starter 15 at 125 kg/ha.

On areas of sodic clay soils, broadcast gypsum at 500 kg/ha to reduce surface crusting (don't incorporate).

**Table 5.41.** Pasture sowing recommendations for Class 3 sites (severely saline), >8 dS/m ECe

Appearance: large bare areas.

Species	Sowing rate (kg/ha)
Tall wheat grass	6–10
Puccinellia	2–4
Palestine strawberry clover	2–3
<i>Total</i>	10–17

**Fertiliser**

Use a nitrogen and phosphorus mixture with sulfur present, e.g. Starter 15 at 125 kg/ha.

On areas of sodic clay soils, broadcast gypsum at 500 kg/ha to reduce surface crusting (incorporation is not recommended) (see Francis and Marcar 1993).

### 5.9.6 Field indicators of salinity

The following salinity indicators were formulated by the Soil Conservation Service of NSW (1990).

1. Trees die for no apparent reason.
2. Productive annual and perennial species thin and die out. They are replaced by more salt-tolerant plants.
3. Soil becomes waterlogged. This is one of the first signs of a potential salinity problem. However, not all waterlogging will result in the development of salinity.
4. Bare patches of soil appear, become progressively larger and easily erode.
5. Stock congregate on an area and lick the surface.
6. Salt crystals are visible when the soil surface is dry.
7. The surface of the bare soil is 'puffy' to walk on when dry.
8. Excess quantities of runoff flow from the area causing erosion of the site and the area downhill.
9. Water in a dam is very clear, because the salt settles the sediment.
10. Smell of salt.

### 5.9.7 Composition of seawater

The composition of seawater varies with inputs of freshwater and the degree of evaporation and mixing that occurs with the ocean (Encyclopaedia Britannica 1991). However, some general average properties are presented here for comparison to saline waters encountered in areas of terrestrial salinity.

#### (i) pH 7.4–8.3

#### (ii) Electrical conductivity (see Table 5.42)

**Table 5.42.** Electrical conductivity of seawater

Value	Unit
50.0–55.0	dS/m
50.0–55.0	mS/cm
50 000–55 000	µS/cm
50 000–55 000	EC
50.0–55.0	mmho/cm
32 000–35 200	total dissolved solids (TDS) (mg/L)
32 000–35 200	total dissolved solids (ppm) (mg/L)

**(iii) Levels of cations and anions** (see Table 5.43)**Table 5.43.** Levels of cations and anions in seawater\*, assuming a density of seawater of 1.025 g/cm<sup>3</sup> at 20°C.

Ion	grams of ion per kg of seawater (g/kg)*	parts per million or milligrams of ion per kilogram of seawater (ppm or mg/kg)	millimoles of ion per kilogram of seawater (mmol/kg)	millimoles of ion per litre of seawater* (mmol/L)	milliequivalent of ion per litre of seawater (mequiv/L)
Cl <sup>-</sup>	19.162	19162	540.5	554	554
Na <sup>+</sup>	10.679	10679	464.5	476	476
Mg <sup>2+</sup>	1.278	1278	52.6	53.9	107.8
SO <sub>4</sub> <sup>2-</sup>	2.68	2680	27.9	28.6	57.2
Ca <sup>2+</sup>	0.496	496	10.2	10.5	21.0
K <sup>+</sup>	0.396	396	10.1	10.4	10.4
Br <sup>-</sup>	0.0663	66.3	0.83	0.85	—
B	0.0044	4.4	0.41	0.42	—
Sr	0.0079	7.9	0.09	0.09	—
F <sup>-</sup>	0.0013	1.3	0.07	0.07	—
HCO <sub>3</sub> <sup>-</sup>	0.140	140	2.29	2.25	2.25
CO <sub>3</sub> <sup>2-</sup>	0.018	18	0.30	0.29	0.58
Total	35	35000	—	—	—

**(iv) Levels of inorganic carbon, nitrogen and phosphorus**

The level of inorganic carbon is about 0.0276 g/kg of seawater or 27.6 ppm. This is equivalent to 2.4 mmol/kg of seawater or 2.4 mmol/L of seawater. Much of the inorganic carbon content is a consequence of CO<sub>2</sub> dissolving in seawater to give HCO<sub>3</sub><sup>-</sup> and CO<sub>3</sub><sup>2-</sup> ions, with about 90% being in the form of HCO<sub>3</sub><sup>-</sup>, depending on the pH of the seawater.

The level of inorganic nitrogen in seawater varies from 0.001–0.045 mmol/kg of seawater. This is equivalent to 0.014–0.63 mg/kg or ppm. This level varies according to the level of biological activity in the water, temperature and currents. The nitrogen occurs as NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup>.

The level of inorganic phosphorus in seawater varies from  $<1.0 \times 10^{-4}$  to  $5 \times 10^{-4}$  mmol/kg at the surface, to  $3 \times 10^{-3}$  mmol/kg in the deeper ocean. This is equivalent to  $3.1 \times 10^{-3}$  to  $1.55 \times 10^{-2}$  mmol/kg, i.e. 0.0031 ppm to 0.016 ppm. At depth, the level of phosphorus increases to  $3 \times 10^{-3}$  mmol/kg, i.e. equivalent to 0.093 ppm. The phosphorus occurs as PO<sub>4</sub><sup>3-</sup> and HPO<sub>4</sub><sup>2-</sup>.

**(v) The sodium adsorption ratio (SAR)**

For seawater, the sodium adsorption ratio (see Section 5.10) is given by:

$$\frac{476}{\sqrt{(53.9 + 10.5)}} = 59.31.$$

### 5.9.8 Relative dissolution rates of different minerals

While rock weathering is only one source of salts in the landscape, it can be a significant source. The other source of salt includes atmospheric deposition associated with wind, rainfall and dust (McKenzie *et al.* 1994). Table 5.44 gives an indication of the potential for the different rock minerals to supply salts.

**Table 5.44.** Relative rates of dissolution of different minerals in laboratory experiments at pH 5 from equilibrium (Drever and Clow 1995 in Taylor and Eggleton 2001)

\*, based on molarity and Weast (1974).

Mineral group	Mineral	Relative dissolution rate
Silica	Quartz	0.02
Mica	Muscovite	0.22
	Biotite	0.6
Alkali–feldspar	Microcline (K–feldspar)	0.6
	Sanidine (K–Na feldspar)	2
Plagioclase	Albite (Na 100%, Ca 0%)	1
	Oligoclase (Na 80%, Ca 20%)	1
	Andesine (Na 60%, Ca 40%)	7
	Bytownite (Na 20%, Ca 80%)	15
Pyroxene	Enstatite	57
	Diopside	85
Olivine	Forsterite	250
Carbonate	Dolomite	360 000
	Calcite	6 000 000
Sulfate	Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )	*600 000 000
	Epsom salts ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ )	* $1.23 \times 10^{11}$
Chloride	Halite (sodium chloride)	* $8.08 \times 10^{11}$
	Calcium chloride	* $2.87 \times 10^{11}$

### 5.9.9 Key references

Richards (1954); Ayers (1977); Soil Conservation Service of NSW (1990); Encyclopaedia Britannica (1991); Taylor (1991); Rhoades *et al.* (1992); Francis and Marcar (1993); Slavich and Petterson (1993); Ayers and Westcott (1994); Shaw (1999); Taylor and Eggleton (2001).

## 5.10 Soil sodicity

### 5.10.1 Identifying sodic soils

Sodicity occurs when exchangeable sodium on the cation-exchange complex leads to clay dispersion in the soil. Small amounts of exchangeable sodium can have a big effect on

clay dispersion when soils become wet. The distribution and occurrence of sodic soils in Australia are described in Naidu *et al.* (1995). Sodic soils have the following problems:

- very severe surface crusting
- very low infiltration and hydraulic conductivity
- very hard, dense subsoils
- high susceptibility to severe gully erosion
- high susceptibility to tunnel erosion.

The level of exchangeable sodium can be determined directly by measuring the concentration of all the exchangeable cations in the soil and expressing the amount of exchangeable sodium,  $\text{Na}_x$  (cmol/kg), as a proportion of the sum of all the exchangeable cations (known as the *cation exchange capacity*, CEC). This proportion is called the *exchangeable sodium percentage* (ESP) and is calculated as follows:

$$\text{ESP} = 100 \text{Na}_x / \text{CEC}$$

where the CEC is taken to be the sum of all the exchangeable cation-concentrations expressed in cmol/kg. Note that if you are provided with exchangeable cation data for your soil in units other than cmol/kg, you must convert them to obtain meaningful information about ESP and sodicity.

Three categories of sodicity corresponding to different ESPs are shown in Table 5.45.

**Table 5.45.** Sodicity and ESP

Sodicity rating	ESPs proposed for Australian soils (Northcote and Skene 1972)	ESPs proposed for NSW soils (Pope and Abbot 1989)
Non-sodic	0–6	0–5
Marginally sodic to sodic	6–14	5–10
Strongly sodic	>14	>10

Sodicity can also be determined indirectly by measuring the concentrations of all cations contained in the soil solution (either a saturated paste extract or a 1:5 soil/water suspension). These concentrations can be used to calculate the *sodium adsorption ratio*, SAR, which describes the activity of the sodium ion relative to that of calcium and magnesium, as follows:

$$\text{SAR} = [\text{Na}^+] / \{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]\}^{\frac{1}{2}}$$

in which all cation concentrations are expressed in mmol/L. These must be calculated from laboratory results (which are often expressed in mg/L) by dividing these concentrations by the atomic weights (mg/mmol) for each cation.

If there are high levels of carbonates and bicarbonates in the soil water, Rayment and Higginson (1992) recommend that the SAR be adjusted to account for the gradual precipitation of calcium and magnesium at higher pHs, as follows:

$$\text{SAR}_{\text{adj}} = \text{SAR} (9.4 - \text{pH}_c)$$

in which  $\text{pH}_c$  is a calculated pH based on the measured concentrations of Na, Ca, Mg, carbonate and bicarbonate in solution.

The correlation between ESP and SAR depends upon whether the SAR is calculated from cation concentrations determined from saturated paste extracts or from 1:5 soil/water suspensions. For cation concentrations measured on paste extracts the approximate correlation,  $ESP \approx SAR$ , is a fairly reliable rule of thumb, which means that a soil is sodic if  $SAR_{se} > 5$  to 6. For cation concentrations measured on 1:5 soil/water suspensions, the approximate correlation,  $ESP \approx 2 SAR$ , is often used, which means a soil is sodic if  $SAR_{1:5} > 2.5$  to 3. Rengasamy *et al.* (1984) produced a set of more precise correlations for some sandy texture-contrast soils of Australia and these are shown in Figure 5.2, but the rules of thumb outlined above are sufficient for most purposes.

The effects of ESP and SAR on soil physical behaviour (e.g. permeability) are controlled to a large extent by the concentration of soluble salts in the soil solution, which can be measured directly as the total cation concentration (TCC, mmol(+)/L), which comprises the sum of all positive charges in the soil solution. The contribution to positive charge from monovalent cations such as  $Na^+$  and  $K^+$  is simply the sum of the concentrations of each cation in mmol/L. The contribution from polyvalent cations such as  $Ca^{2+}$  and  $Mg^{2+}$  is the sum of the products of the concentrations of each cation and their respective valence.

The total cation concentration of a soil solution can also be determined indirectly by measuring the electrical conductivity of the soil solution (EC, dS/m). The relationship between cation concentration (mmol(+)/L) and EC (dS/m) is linear for solutions with  $EC < 10$  dS/m and can be expressed as:

$$TCC \text{ (mmol(+)/L)} \approx 10 \text{ EC (dS/m)}$$

An example of some typical information provided in a soil test result, plus the information that can be derived from it, is shown in Table 5.46.

**Table 5.46.** Information provided in a soil test result for a loam-textured soil

	Solution	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>
Concentration 1:5 soil/water extract (mg/L)		135	19	8	2
Electrical conductivity 1:5 soil/water extract dS/m	0.75				
pH of 1:5 soil/water extract	8.84				
	Information derived from the soil test data:				
Atomic weight of cation (g/mol or mg/mmol)		23	39	40	24
Concentration (mmol/L)		5.87	0.487	0.200	0.0833
SAR	$5.87 / (0.200 + 0.0833)^{\frac{1}{2}} = 11.03$				
ESP from SAR 1:5 soil/water suspension	22.06				
TCC of 1:5 soil/water extract (mmol(+)/L)	$5.87 + 0.487 + 2 \times 0.200 + 2 \times 0.0833 = 7.46$				
TCC (mmol(+)/L) calculated from EC (dS/m)	7.5				

You can see from the high SAR (~11) that the soil is quite sodic (ESP ~22). This is not surprising, of course, when you look at how alkaline the soil pH is. In general, the only significant cation that occurs in alkaline solutions is sodium.

Both estimates of the total cation concentration (from summing the cations and by measuring EC) are quite similar (approximately 7.5 mmol(+)/L). For most soils, any total cation concentration > 7 mmol(+)/L reflects a saline condition.

The critical ESP above which dispersion tends to occur depends on the EC of the soil water solution and the amount of work or energy applied to the soil. For example, dispersion can occur for surface soils with ESP < 3 under rainfall because the rainfall generally has a very low EC and raindrop impact on bare soil imparts significant energy on the soil. A modest EC is sometimes preferred for irrigation of mildly sodic surface soils, as this reduces dispersion and surface sealing or crusting. While the *Australian Soil Classification* (Isbell 1996) identifies Sodosols as soils having ESP > 6 in the upper part of the B horizon, other soils display sodic behaviour with different ESPs in different horizons.

### 5.10.2 Emerson aggregate class and sodicity

The Emerson aggregate test can be used as a general guide to sodicity (see Table 5.47). The aggregate test can be used only as a general guide because of the large number of factors that determine whether dispersion occurs, such as sodicity, salinity, clay type, history of working and speed of wetting. Other aggregate tests used in the field include modified aggregate tests such as Loveday and Pyle (1973) and Field *et al.* (1997). These are semi-quantitative modifications to the original Emerson Test and the Field *et al.* (1997) Test and have the advantage of providing a rapid assessment in the field.

**Table 5.47.** A general guide to the relationship between sodicity and the Emerson aggregate class  
(See also Section 2.6.4.)

Emerson aggregate class	Sodicity
Class 1 and 2(3)	almost certainly sodic
Class 2(2)	highly likely to be sodic
Class 2(1)	may be sodic
Classes 3(4), 3(3)	may be sodic
Classes 3(2), 3(1)	unlikely to be sodic
Class 4	may be sodic
Class 5	unlikely to be sodic
Class 6	almost certainly non-sodic

Adapted from Murphy (1995).

These are generalised ratings and are only a guide that assumes salinity levels are low.

### 5.10.3 Dispersion, sodicity and salinity

As explained above, the TCC can greatly influence whether dispersion occurs in a soil. Relationships were derived by Rengasamy *et al.* (1984) using 1:5 soil/water extracts for surface soils of red-brown earths. These can be used as a guide for the dispersive behaviour of many soils (see Figure 5.2).

#### Explanation of classes in Fig. 5.2

**Class 1.** Dispersive soils that disperse spontaneously in water. These are unstable, sodic soils that can have severe management and erosion problems.

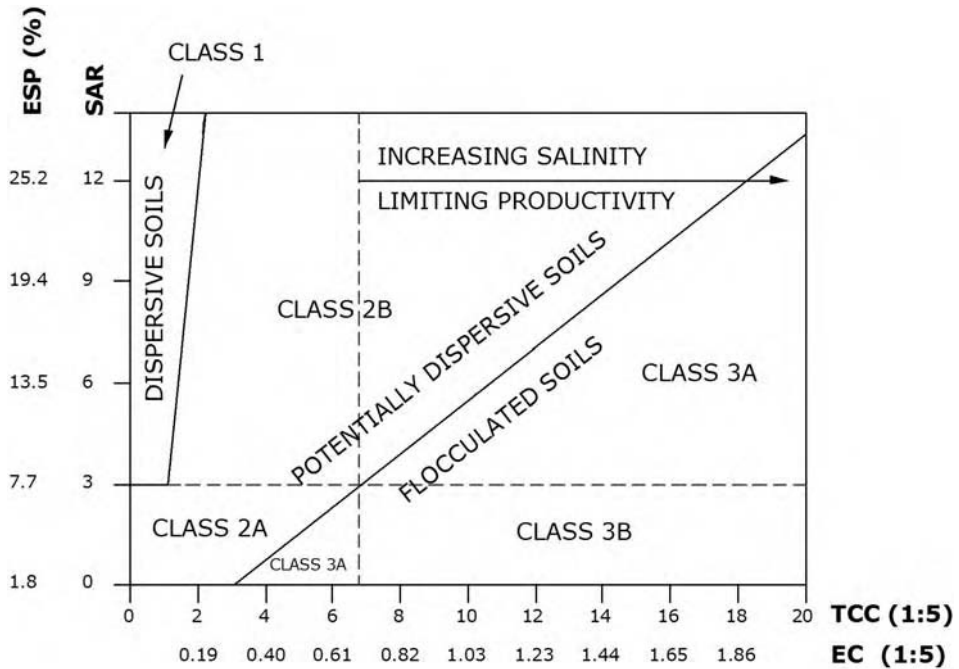


Fig. 5.2. Predicting soil dispersion based on exchangeable sodium percentage (ESP) and electrical conductivity of the soil (EC1:5).

**Class 2.** Potentially dispersive soils that disperse after the application of mechanical work either by raindrop impact, irrigation or tillage. This was simulated by one hour of end to end shaking in the laboratory.

**Class 2a.** Soils that have few structural problems if managed using minimum tillage techniques or if maintained under continuous pasture growth.

**Class 2b.** Unlike Class 2a soils, these soils become spontaneously dispersive (Class 1) when leached without the addition of calcium compounds, and if there is no generation of electrolytes in the soil due to mineral weathering.

**Class 3.** Flocculated soils that remain flocculated, even when subjected to mechanical stress.

**Class 3a.** Leaching with low electrolyte water may change saline-sodic soil to Class 2b, or in extreme leaching to Class 1. Soils may then disperse and cause severe crusting.

**Class 3b.** These soils are saline but dominated by non-sodium salts. These soils have no physical problems and the amount of leaching required depends on the salt tolerance of crops to be grown.

**Class 3c.** No dispersion and salinity problems occur where total cation concentration (TCC) is greater than 20.

For a full explanation of these classes, see Rengasamy *et al.* (1984).

### Versatility of the relationships

The relationship shown in Fig. 5.2 is specific for the surface soils of red-brown earths in south-eastern Australia, particularly in northern Victoria, South Australia and southern New South Wales.



However, the lines that show the division between the dispersed and flocculated states of the soil are dependent on many factors, including:

- presence of  $\text{CaCO}_3$
- Ca:Mg ratio
- iron and aluminium oxides
- severity of drying and degree of hardsetting
- presence of organic matter
- exchangeable aluminium and pH
- clay type or mineral composition of the soil.

Figure 5.2 should be applied with care to conditions and soils other than those from which the diagram was derived. In particular, Rengasamy *et al.* (1984) maintain that further work is required to establish useful relationships between SAR, TCC and soil physical problems in sub-surface soils (see Fig. 2 in Rengasamy *et al.* (1984)). Figure 31 in Sumner (1993) shows how different factors can affect the relationship.

#### 5.10.4 Sodicity and pH

There is a general relationship between sodicity and pH above a pH of 8.0 in 1:2 soil/water suspension, as shown in Table 5.48.

**Table 5.48.** Relationship between sodicity and pH  
ESP, exchangeable sodium percentage.

pH 1:2 soil/water suspension	ESP
8.2–9.0	<20
9.0–9.4	21–35
9.4–9.6	35–50
9.6–9.8	50–65
9.8–10.0	65–85
>10.0	>85

Source: Gupta and Abrol (1990).

High levels of ESP are usually associated with high pH because  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$  ions precipitate the  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions out of the solution.

#### 5.10.5 Key references

Richards (1954); Northcote and Skene (1972); Rengasamy *et al.* (1984); Pope and Abbott (1989); Gupta and Abrol (1990); Abbott (1991); McKenzie *et al.* (1993); Naidu *et al.* (1995); Sumner (1993); Rengasamy and Churchman (1999).

#### 5.10.6 Further reading

Sumner and Naidu (1998).

## 5.11 Fertilisers and soil ameliorants

### 5.11.1 General fertilisers and ameliorants

The brand names of fertilisers listed in Table 5.49 are examples only, and their inclusion does not imply a recommendation for their use.

**Table 5.49.** Nutrient levels in various fertilizers for winter cereals

Name	P%	Rate of fertiliser to apply 10 kg	N%	Rate of fertiliser to apply 5 kg N/ha	S%	Rate of fertiliser to apply 5 kg S/ha	K%	Rate of fertiliser to apply 5 kg K/ha
DAP®	20	50	18	28	1.6	313	0	na
MAP®	22	45	10	50	1.5	333	0	na
Super®	8.8	114	0		11	45	0	na
BigN®	0	na	82	6	0	na	0	na
Granular urea®	0	na	46	11	0	na	0	na
Legume Starter	15.5	65	5.1	98	6.8	74	0	na
Sulfate of ammonia	0	na	20.5	24	24	21	0	na
Blood and bone	5	na	6.8	74	0	na	0	na
Sulfos	13.7	73	0	na	7	71	0	na
Super Plus	8.2	122	0	na	17.2	29	0	na
Nitram 50/50	0	na	20.4	25	0	na	20	25

Source: Incitec Pivot, Newcastle, and local fertiliser dealers.

**Table 5.50.** Nutrient contents of various fertiliser products (Bumb and Hammond 2002)

Fertiliser products	Nitrogen content (%)	Phosphate content (%)	Potassium content (%)
<b>Multinutrient fertilisers:</b>			
Mono-ammonium phosphate (MAP)	11	29	—
Di-ammonium phosphate (DAP)	18	26	—
Urea ammonium phosphate	28–32	17	—
<b>Nitrogen fertilisers:</b>			
Anhydrous ammonia	82	—	—
Ammonium sulfate	21	—	—
Ammonium chloride	26	—	—
Calcium nitrate	16	—	—
Sodium nitrate	16	—	—
Ammonium nitrate	34	—	—
Ammonium nitrate sulfate	26	—	—
Calcium ammonium nitrate	21	—	—
Urea	46	—	—
S-coated urea	35	—	—
<b>Phosphate fertilisers:</b>			
<i>a. Water soluble</i>	—	—	—
Single super (SSP)	n/a	10	—
Double super (DAP)	—	26	—
<i>b. Slow acting phosphates</i>	—	—	—
Dicalcium phosphate	—	23	—
Rock phosphate	—	18	—
<b>Potassium fertilisers:</b>			
Muriate of potash (potassium chloride)	—	—	50
Potassium nitrate	13	—	37
<b>Forms in which nutrients are taken up by plants:</b>	$\text{NH}_4^+, \text{NO}_3^-$	$\text{H}_2\text{PO}_4^-$	$\text{K}^+$
Sulfur	$\text{SO}_4^{2-}$	—	—
Magnesium	$\text{Mg}^{2+}$	—	—
Calcium	$\text{Ca}^{2+}$	—	—
Copper	$\text{Cu}^{2+}$	—	—
Zinc	$\text{Zn}^{2+}$	—	—
Molybdenum	$\text{MoO}_4^{2-}$	—	—

**Table 5.51.** Solubilities of compounds commonly used as soil ameliorants compared with those of other naturally occurring compounds

Compound	Form	Formula	Solubility (g/L water)	Molecular weight of compound (g/mol)	Molar solubility (mmol/L H <sub>2</sub> O)
Calcium chloride	—	CaCl <sub>2</sub>	745	110.99	6710
Calcium sulfate	gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	2.41	172.17	14
	plaster of Paris	CaSO <sub>4</sub> ·0.5H <sub>2</sub> O	3.00	145.15	21
	anhydrite	CaSO <sub>4</sub>	2.09	136.14	15
Calcium carbonate (agricultural lime)	calcite	CaCO <sub>3</sub>	0.014	100.09	0.14
	aragonite	CaCO <sub>3</sub>	0.015	100.09	0.15
Dolomite	—	CaMgCO <sub>3</sub>	0.32	184.41	1.7
Magnesium chloride	—	MgCl <sub>2</sub>	542.5	95.22	5700
Magnesium carbonate	magnesite	MgCO <sub>3</sub>	0.106	84.32	1.3
Magnesium sulfate	—	MgSO <sub>4</sub>	260	120.37	2160
	Epsom salts	MgSO <sub>4</sub> ·7H <sub>2</sub> O	710	246.48	2880

Source: Weast (1974).

These are the solubilities of pure forms of these compounds, and all commercially available forms of these compounds will not necessarily have the degree of solubility shown here because of impurities. The solubility will also be influenced by particle size, especially for those compounds that are sparingly soluble such as calcium carbonate.

### 5.11.2 Forms of gypsum

Most gypsum sold in NSW is CaSO<sub>4</sub>·2H<sub>2</sub>O that has 18.6% S when completely pure (Abbott and McKenzie 1986). Therefore the sulfur content can be used to define the purity of gypsum. The water content is also an important factor in the quality of gypsum (see Tables 5.52–5.53).

**Table 5.52.** Sulfur content of gypsum

Purity reading	%S	Equivalent % CaSO <sub>4</sub> ·2H <sub>2</sub> O	Likely source
Low	<12.0	<65	cannot be registered for sale in NSW
Medium	12.0–14.0	65–75	mostly mined gypsums
High	14.1–16	76–86	mostly by-product gypsums
Very high	16.1–18.6	87–100	some mined and by-product gypsums
Extremely high	18.7–23.5	101–126	form of gypsum is probably CaSO <sub>4</sub> not CaSO <sub>4</sub> ·2H <sub>2</sub> O

**Table 5.53.** Water content of gypsum

Water content rating (%)	Rating	Likely source
0–5	low	most mined gypsums, some by-product gypsums
6–10	medium	some by-product gypsums
11–15	high	some by-product gypsums
>15	very high	cannot be registered for sale in NSW

Source: Abbott and McKenzie (1986).

Gypsum must also meet requirements of fineness (percentage passing through a 2 mm sieve) and chloride content (see Abbott and McKenzie 1986).

### 5.11.3 Liming materials

#### Neutralising Value (NV)

The capacity of a liming material to neutralise soil acidity is expressed as Neutralising Value. The higher the NV the greater is the ability of the product to correct the acidity. Pure lime, pure calcium carbonate, is taken as the standard with an NV of 100. Hydrated (slaked) lime and burnt (quick) lime have NVs of 120 and 160 respectively.

Liming materials are used to neutralise soil acidity (Fenton *et al.* 1993). A full explanation of liming materials is presented in Agfact AC.15, 'Liming materials' (Weir 1987). The properties of some commonly used liming materials are given in Table 5.54.

**Table 5.54.** The properties of some commonly used liming materials

Liming material	Neutralising value (NV)			Calcium (%)			Magnesium (%)		
	Pure form	Commercial grades		Pure form	Commercial grades		Pure form	Commercial grades	
		Good	Poor		Good	Poor		Good	Poor
Agricultural lime (CaCO <sub>3</sub> )	100	95–98	60–75	40	36–39	28–32	0	<1	–
Dolomite (MgCaCO <sub>3</sub> )	109	92–102	60–75	22	21	10–15	13	12	4–7
Magnesite (MgCO <sub>3</sub> )	119	95–105	–	0	0.5–1.0	–	28.6	20–28	–
Hydrated lime (Ca[OH] <sub>2</sub> )	135	110–120	<105	54	44–49	<40	0	<1	–

Source: Fenton *et al.* (1993).

The fineness of lime is critical for its effectiveness. The lime material passing through a 0.25 mm sieve is the most active component. The effectiveness of a liming material is defined as:

$$\text{Effectiveness} = \frac{\% \text{ passing } 0.25 \text{ mm sieve} \times \text{NV}}{100}$$

## 5.12 General fertility rating of soils in Australia

The relative fertilities of NSW soils based on the Great Soil Groups Australian Soil Classification is shown below. Names based on Isbell (1996) are also added. Soils are ordered from low to high fertility.

<i>Group 1</i>	Low fertility
Solonchaks (Hypernatric Sodosols)	
Lithosols (Lithic Rudosols)	
Calcareous sands (Calcareous Tenosols)	
Siliceous sands (Tenosols)	
Earthy sands (Tenosols)	
Grey brown and red calcareous soils (Calcarosols)	
Ironstone gravels (Ferric Tenosols)	
<i>Group 2</i>	
Solodised solonetz and solodic soils (Sodosols)	
Solods (Sodosols, Kurosols)	
Red earths (Red Kandosols)	
Yellow earths (Yellow Kandosols, Yellow Kurosols)	
Solonised brown soils (Calcarosols)	
Yellow podzolic soils (Yellow Chromosols, Yellow Kurosols)	
Lateritic podzolic soils (Ferric Chromosols)	
Podzols (Podosols)	
Acid grey earths (Grey Kurosols)	
Acid bleached grey earths (Grey Kurosols)	
<i>Group 3</i>	
Grey, brown and red clays (Vertosols)	
Red-brown earths (Red Chromosols)	
Non-calcic brown soils (Red Chromosols, Red Dermosols)	
Terra rossa soils (Red Dermosols)	
Xanthozems (Yellow Dermosols)	
Red podzolic soils (Red Chromosols)	
Alpine humus soils (Chernic Tenosols)	
Humic gleys (Hydrosols)	
Deep red and yellow friable loams (Dermosols)	
<i>Group 4</i>	
Chocolate soils (Brown Dermosols, Brown Ferrosols)	
Euchrozems (Red Ferrosols, Red Dermosols)	
Krasnozems (Red Ferrosols)	
<i>Group 5</i>	
Black earths (Black Vertosols)	
Chernozems (Black Dermosols)	
Prairie soils (Black Dermosols)	High fertility

Source: Charman (1978); Murphy *et al.* (2000).

**Table 5.55. Nutrient availability**

\*, the rating is determined by that of the most limiting characteristic. \*\*, estimated by field data on the nature and content of gravels by laboratory analyses of reactive iron (Class limits. Yeates, personal communication 1980); \*\*\*, references: Charman (1978) and Bruce and Rayment (1982).

Characteristics	Rating*		
	High	Moderate	Low
Soil reaction (pH)	neutral or mildly alkaline (6.0–7.5)	mildly acid or alkaline (5.0–6.0 or 7.5–8.5)	strongly acid or alkaline (<5.0 or >8.5)
Ferric oxide** Fe <sub>2</sub> O <sub>3</sub> content***	nil Fe gravels or reactive Fe <300 ppm	very few few (<10%) Fe gravels, or reactive Fe 3000–1000 ppm	common or more than 10% Fe gravels, or reactive Fe >1000 ppm
Soil colour and texture trend (broad soil types)	dark coloured uniform loams, clays or gradational earths	red, yellow and brown duplex soils or gradational earths	highly leached, pale or bleached sands calcareous soils, duplex soils with bleached sub-surface A2 horizons
Cation exchange capacity (cmol[+]/kg)	>25	15–25	<15
Organic matter	% organic C >2.5 or very dark soil colour, value chroma (V/C) rating	% organic C 1.5–2.5, or reddish brown soil colours, V/C rating 5	% organic C <1.5 or yellowish grey soil colours, V/C rating 2, 3, 4

Source: Cregan (1980).

## 5.13 Acid sulfate soil

Acid sulfate soils occur predominantly on coastal lowlands with elevations generally below 5 m Australian Height Datum (AHD). When these lowlands are disturbed by excavation or drainage, toxic quantities of acid are released. As the pH drops below 4.5, aluminium, iron and other heavy metals may be released which may contaminate land and adjacent waterways, killing aquatic flora and fauna in the natural environment. In developed areas, infrastructure such as pipes and foundations are susceptible to corrosion. This soil also has a low wet bearing strength.

Information on the analysis, interpretation of results, management and risk assessment for acid sulfate soil is being continuously updated. It is important, therefore, that references such as the *Queensland Acid Sulfate Soil Technical Manual* (ASMAC), available on the Internet, or research findings in your local regional area are consulted.

### 5.13.1 Composition of seawater and acid sulfate soils

Seawater contains 2700 mg SO<sub>4</sub><sup>2-</sup>/kg, which is 28 mmol of SO<sub>4</sub><sup>2-</sup>/L. This amount of SO<sub>4</sub><sup>2-</sup> gives the potential for acid sulfate soils to develop in marine and estuarine environments (Melville and White 2007).

### 5.13.2 Laboratory analyses

The SPOCAS method and its components, along with chromium reducible sulfur, acid volatile sulfur and acid neutralising capacity methods, are the most relevant ASS testing methods and are currently being compiled in association with Standards Australia with the intention of producing a united set of laboratory methods (in the form of Australian Standards) that will be applicable nationwide. (See Ahern *et al.* 2004).

### 5.13.3 Field peroxide test

The field peroxide test is a useful exploratory tool indicating Potential Acid Sulfate Soil (PASS), but is indicative only, and definitely not quantitative. It is not a replacement for quantitative laboratory analyses. It is least useful on low analysis sands and on highly organic soils and coffee rock.

The pH is measured on an untreated sub-sample to give  $\text{pH}_F$ , and then hydrogen peroxide is added and pH measured to obtain  $\text{pH}_{\text{FOX}}$ .

Three factors are considered in arriving at a 'positive field sulfide indication':

- The strength of the reaction with peroxide is a useful indicator. Organic matter and manganese oxides can also cause a reaction so care must be exercised in interpreting a reaction on soils with high organic matter content.
- A  $\text{pH}_{\text{FOX}}$  value at least one unit below field  $\text{pH}_F$  may indicate a PASS. The greater the difference between the two measurements, the more indicative the value is of a PASS.
- If the  $\text{pH}_{\text{FOX}} < 3$ , and the other two conditions apply, then it indicates a PASS. The more the  $\text{pH}_{\text{FOX}}$  drops below 3, the more likely the presence of sulfides.

### 5.13.4 Interpreting values for acid sulfate soil tests

#### Cl/SO<sub>4</sub> ratio

A Cl/SO<sub>4</sub> ratio of  $< 4$  in groundwater indicates a probable ASS source.

#### Action criteria

The action criteria in Table 5.56 trigger the need in NSW to prepare a management plan and are based on the percentage of oxidisable sulfur (or equivalent TPA, TAA) for broad categories of soil types.

**Table 5.56.** Action criteria based on ASS soil analysis for three broad texture categories (from Ahern *et al.* 1998)

Type of material		Action criteria if 1–1000 tonnes disturbed		Action criteria if more than 1000 tonnes disturbed	
Texture range (McDonald <i>et al.</i> 1990)	Approximate clay content (% $< 0.002$ mm)	Sulfur trail %S oxidisable (oven-dry basis) eg STOS or SPOS	Acid trail mol H <sup>+</sup> /tonne (oven-dry basis) eg TPA or TSA	Sulfur trail %S oxidisable (oven-dry basis) eg STOS or SPOS	Acid trail mol H <sup>+</sup> /tonne (oven-dry basis) eg TPA or TSA
Coarse texture Sands to loamy sands	$\leq 5$	0.03	18	0.03	18
Medium texture Sandy loams to light clays	5–40	0.06	36	0.03	18
Fine texture Medium to heavy clays and silty clays	$\geq 40$	0.1	62	0.03	18



## Acid sulfate soil liming conversions

Conversions between some of the common units used to express analytical results from acid sulfate soils are given in Table 5.57. The conversions are based on 1 mole pyrite producing 2 moles of sulfuric acid or 4 moles of  $H^+$  with the equivalent liming rates using a safety factor of 1.5.

**Table 5.57.** Conversions for some units of reporting acid sulfate soils analysis (from Ahern *et al.* 2004)

Net acidity Sulfur units (% pyrite S)	Net acidity mol $H^+$ /kg (%S $\times$ 0.6237)	Net acidity mol $H^+$ /t or (mol $H^+$ /m <sup>3</sup> ) (%S $\times$ 623.7)	kg $CaCO_3$ /t soil or (kg $CaCO_3$ /m <sup>3</sup> ) (mol $H^+$ /t)/19.98) No safety factor	kg $CaCO_3$ /t soil or (kg $CaCO_3$ /m <sup>3</sup> ) (mol $H^+$ /t)/13.32) Safety factor = 1.5
0.01	0.0062	6.237	0.312	0.45
0.03	0.0187	18.71	0.936	1.40
0.06	0.0374	37.42	1.87	2.81
0.1	0.0624	62.37	3.12	4.68
0.2	0.1247	124.7	6.24	9.36
0.3	0.1871	187.1	9.36	14.0
0.5	0.3119	311.9	15.6	23.4
1.0	0.6237	623.7	31.2	46.8
2.0	1.2474	1247	62.4	93.6
5.0	3.1185	3119	156	234

Table 5.58 allows estimation of the quantity of lime involved if the total volume/mass of acid sulfate soils to be disturbed is known and soil analysis has been performed. The table is based on the quantity of lime required to neutralise the acid that could potentially be produced and includes the minimum industry safety factor of 1.5.

**Table 5.58.** Estimating treatment levels and agricultural lime needed to treat the total weight of soil disturbed (adapted from Ahern *et al.* 1998)

See Ahern *et al.* (1998) for the strict guidelines needed when applying these criteria. \*, bulk density  $\times$  soil volume.

Amount of disturbed acid sulfate soil* (tonnes)	Existing acidity and potential acidity converted to equivalent oxidisable S (%) (tonnes of agricultural lime to neutralise acidity)						
	0.03	0.1	0.4	0.6	1	2	5
5	0	0	0.1	0.1	0.2	0.5	1.2
50	0.1	0.2	0.9	1.4	2.3	4.7	12
100	0.1	0.5	1.9	2.8	4.7	9.4	23
500	0.7	2.3	9.4	14	23	47	117
750	1.1	3.5	14	21	35	70	176
1000	1.4	4.7	19	28	47	94	234
2000	2.8	9.4	37	56	94	187	468
5000	7.0	23	94	140	234	468	1170
10 000	14	47	187	281	468	936	2340

Treatment levels: Low treatment, <0.1 tonne lime; medium treatment, >0.1 to 1.0 tonne lime; high treatment, >1 to 5 tonnes lime; very high treatment, >5 to 25 tonnes lime; extremely high treatment, >25 tonnes lime.

The formula to calculate liming rates is:

$$\%S \times 30.59 \times 1.02 \times 1.5 = \text{kg CaCO}_3/\text{tonne of soil}$$

Note: 30.59 converts to  $\text{H}_2\text{SO}_4$ ; 1.02 converts to  $\text{CaCO}_3$ ; and 1.5 is the safety factor.

To convert units from tonnes to cubic metres, multiply the kg  $\text{CaCO}_3$ /tonne of soil by the bulk density.

To change units from %S to mol  $\text{H}^+$ /tonne, multiply the %S by 623.7.

### 5.13.5 Key references

Ahern *et al.* (1998); Dear *et al.* (2002); Melville and White (2000); Ahern *et al.* (2004).

### 5.13.6 Further reading

Ahern *et al.* (2004); Dear *et al.* (2002); *Australian Journal of Soil Research* (2004). Special issue: Sustainable Management of Acid Sulfate Soils. Volume 42(5), 42(6).



# 6

## Water analyses relevant to soils

### 6.1 Water quality properties relevant to soils

This is not a comprehensive list of tests used in water analyses; it is limited to those that impact significantly on soil management. Soil or land management can have a significant impact on water quality and it is necessary to have some understanding of several basic tests that are used to evaluate water quality. A more comprehensive description of the interpretation of tests for water quality is presented in ANZECC and ARMCANZ (2000a–c) and NHMRC (2004). These publications have superseded the original publication of ANZECC (1992). A description and interpretation of some basic tests for water quality is presented below. These are likely to be encountered when evaluating the impact on water quality of land management options such as effluent disposal on land, or agriculture. A summary of some of the water quality issues for stream and water storages in NSW is given in Daly and Nancarrow (1998).

#### 6.1.1 Biochemical oxygen demand (BOD)

This is a commonly used method for measuring the quantity of organic material in the water that has a demand for oxygen and is often shortened to BOD. This test is based on the premise that all the biodegradable organic matter contained in a water sample will be oxidised to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  by micro-organisms using molecular oxygen. Organisms utilise oxygen in the process of consuming organic material in the water and this oxygen consumption is easily measured.

The greater the amount of organic matter present, the greater the amount of oxygen utilised. The BOD test is therefore an indirect measurement of organic matter. The  $\text{BOD}_5$  can be calculated from the difference between the dissolved oxygen in mg/L on day one after commencing incubation and the dissolved oxygen (DO) concentration five

days after commencing incubation in mg/L. For this reason it is often written as BOD<sub>5</sub>. This is usually measured in the laboratory under temperature controlled conditions.

Water with a high BOD<sub>5</sub> is likely to cause a depletion of oxygen if it should pollute other water bodies. Typical BOD<sub>5</sub> values for various water sources are shown in Table 6.1.

Table 6.1. Examples of BOD<sub>5</sub> values

Source	BOD <sub>5</sub> mg/L
Raw sewage	150–300
Storm water runoff from residential areas	200–600
Treated sewage	20–30
Unpolluted natural waters	≤5

### 6.1.2 Dissolved oxygen (DO)

DO is ‘free’ oxygen dissolved in water and does not include molecular (bound) oxygen as in H<sub>2</sub>O. It is measured in mg/L. Lack of dissolved oxygen can cause the loss of desirable aquatic organisms (see Table 6.2). Fish generally require oxygen levels of at least 5 mg/L, although some fish such as carp can live with lower oxygen levels (Koehn and O’Conner 1990; Connell 1993). Because the amount of dissolved oxygen in the water varies significantly with temperature, the DO is often expressed as a percentage of the saturation level of oxygen at the temperature when the measurement is made (ANZECC and ARMCANZ 2000*b*). The amount of dissolved oxygen at saturation is higher at cool temperatures so colder waters are usually higher in oxygen.

Table 6.2. Ratings for values of dissolved oxygen

DO (mg/L)	Rating
0–2.9	too low for survival
3.0–4.9	tolerated by coarser fish species, e.g. carp
>5.0	suitable for all fish

Source: Connell (1993).

### 6.1.3 Total phosphate

Total phosphate measures all forms of phosphate in the water including soluble, insoluble, organic and inorganic. High phosphate levels can lead to increased growth of water weeds and algal blooms. An interpretation of the value of total phosphate levels are given in Table 6.3.

**Table 6.3.** Interpretation of phosphate levels in water

Total phosphate level µg/L	Interpretation: The actual trigger value for total phosphate is dependent on several factors including temperature, turbidity and salinity. Hence a range of values is sometimes given.
Sydney Water (2002) and ANZECC (1992) ANZECC and ARMCANZ (2000b: 8, 2.42)	
20	likely to cause increased aquatic plant and algal growth in upland rivers
20–50	likely to cause increased aquatic plant and algal growth in lowland rivers
10	likely to cause increased aquatic plant and algal growth in lakes and reservoirs
35	likely to cause increased aquatic plant and algal growth in estuaries
25	likely to cause increased aquatic plant and algal growth in lowland marine regions
from Bek and Robinson (1991) and Daly and Nancarrow (1998)	
<20	good
20–50	fair
>50	poor

### 6.1.4 Other tests for water quality

Other tests for water quality are discussed in Bek and Robinson (1991), Daly and Nancarrow (1998) and ANZECC and ARMCANZ (2002). These include assessments of macroinvertebrates, faecal coliform bacteria, and counts of the number of cells of blue-green algae, turbidity and salinity. Details on these measurements and their interpretation can be obtained in these publications. Brief guidelines for some of these tests are given in Table 6.4.

### 6.1.5 Key references

US Environmental Protection Agency (1975); Bek and Robinson (1991); ANZECC (1992); Connell (1993); Daly and Nancarrow (1998); ANZECC and ARMCANZ (2000a–c); NHMRC (2004).

## 6.2 Wastewater for irrigation

### 6.2.1 General considerations

The assessment of the suitability of a site for effluent disposal is a specialised field of expertise and account has to be taken of the effluent, soil, landform and hydrological conditions of a site. The guidelines have taken some account of the effluent, soil and landform conditions. No accounts of the hydrology conditions are considered. The assessment of a particular site requires specific information relevant to that site for all the above factors. No assessment should be made with these guidelines alone. Checks should be made with the Environment Protection Authority of NSW, the NSW Department of Land and Water Conservation, and NSW Agriculture about the current guidelines for the application of wastewater to land. For a detailed assessment of the suitability of water for irrigation see ANZECC and ARMCANZ (2000c), which can be viewed on the Department of Environment & Heritage website, and ARMCANZ, ANZECC and NHMRC (2000).

**Table 6.4.** Interpretation of further water tests

NTU, nephelometric turbidity units; <5 is suitable for drinking water; <50 is suitable for aquatic animals and plants.

Test	General guidelines for interpretation
<b>Salinity/electrical conductivity (ANZECC 1992)</b>	
Good	<280 $\mu\text{S}/\text{cm}$ or <0.28 dS/m
Fair	280–800 $\mu\text{S}/\text{cm}$ or 0.28–0.80 dS/m
Poor	>800 $\mu\text{S}/\text{cm}$ or >0.80dS/m
<b>Turbidity (Bek and Robinson 1991)</b>	
Good	<5 NTU (just noticeable in a glass)
Fair	5–50 NTU
Poor	>50 NTU

**6.2.2 Sodium adsorption ratio**

Sodium adsorption ratio is an empirical measure of the sodium imbalance of an industrial waste or soil solution sample. It is a measure of sodium in the infiltrating water, which may tend to deflocculate or disperse the soil (see Section 5.10.2).

The figures in Table 6.5 suggest that wastewater with a SAR value of <8 and  $\text{EC}_\text{e}$  <500  $\mu\text{S}/\text{cm}$  or 0.50 dS/m is likely to be safe in terms of direct effects on plants. However, the results of Rengasamy *et al.* (1984) suggest that SAR values as low as three can still cause dispersion in low electrolyte solutions, and therefore cause soil structural problems (see Section 5.10.2). Where pH is greater than about 8.5, the adjusted SAR can be used (see Section 5.10.4).

**Table 6.5.** Tolerance of crops to sodium

SAR, sodium adsorption ratio.

SAR of irrigation water	Tolerance	Crop	Conditions
2–8	very sensitive	deciduous fruits, nuts, citrus, avocado	leaf tip burn, leaf scorch
8–18	sensitive	beans	stunted growth
18–46	moderately tolerant	clover, oats, tall fescue, rice	stunted because of nutrition and soil structure
46–102	tolerant	wheat, lucerne, barley, tomatoes, beets, tall wheatgrass, crest, wheatgrass	stunted because of soil structure

Source: Hart (1974), ANZECC (1992).

**Table 6.6.** Recommended maximum concentrations of elements in irrigation waters used continuously on all soil types

\*, see Table 6.8; \*\*, pH dependent.

Element	(mg/L or ppm)
Aluminium	5.00
Arsenic	0.10
Beryllium	0.10
Boron	0.75*
Cadmium	0.01
Chromium	0.10
Cobalt	0.05
Copper	0.20
Fluoride	1.00
Iron	1.00
Lead	0.02
Lithium	2.50
Manganese	0.20
Molybdenum	0.01
Nickel	0.20
Selenium	0.02
Zinc	2.00**

Source: Metcalf and Eddy (1991); ANZECC (1992); ANZECC and ARMCANZ (2000c).

**Table 6.7.** Salinity in irrigation water

Municipal wastewaters in NSW usually contain &lt;500 mg/L of total dissolved solids (TDS). The classification based on TDS in this table may be useful when making a preliminary evaluation of a wastewater supply.

Classification of irrigation water	TDS mg/L (ppm)	EC <sub>e</sub> (µS/cm)	EC <sub>e</sub> (dS/m)
Water for which no detrimental effects are usually noticed	<500	<750	0.70
Water that can have detrimental effects on sensitive crops	500–1000	750–1500	0.75–1.50
Water that can have adverse effects on many crops, requiring careful management practices	1000–2000	1500–3000	1.50–3.00
Water that can be used for tolerant plants on permeable soils with careful management practices	2000–5000	3000–7500	3.00–7.50

Source: State Pollution Control Commission (1979).

**Table 6.8.** Acceptable salinity levels in irrigation water: interaction with soils (Bhumbla and Abrol 1972)

Soil type/description	Plant/crop tolerance	Limiting EC for irrigation water (dS/m)
Deep black soils (clay >30%). Fairly to moderately well drained	susceptible tolerant	1.5 2.0
Moderately heavy textured soils (clay 20–30%). Well drained internally and good surface drainage.	susceptible tolerant	2.0 4.0
Medium textured soils (10–20% clay). Well drained internally and good surface drainage.	susceptible tolerant	4.0 6.0
Light textured soils (<10% clay). Excellent internal and surface drainage.	susceptible tolerant	6.0 8.0



**Table 6.9.** Relative tolerance of agricultural crops to boron

Boron in relatively small amounts is essential to the normal growth of plants; however, this element can be toxic in excess. Critical limits are expressed as milligrams of boron per litre of irrigation water.

Tolerance concentration of boron in soil water (mg/L)	Crop
Very sensitive (<0.5)	blackberry, lemon
Sensitive (0.5–1.0)	peach, cherry, plum, grape, cowpea, onion, garlic, sweet potato, wheat, barley, sunflower, mung bean, sesame, lupin, strawberry, Jerusalem artichoke, kidney beans, lime beans
Moderately sensitive (1.0–2.0)	capsicum, pea, carrot, radish, potato, cucumber
Moderately tolerant (2.0–4.0)	lettuce, cabbage, celery, turnip, bluegrass, oat, corn, artichoke, tobacco, mustard, clover, squash, musk melon
Tolerant (4.0–6.0)	sorghum, tomato, alfalfa, purple vetch, parsley, red beet, sugar beet
Very tolerant (6.0–15.0)	asparagus

Source: Westcot and Ayres (1984); ANZECC (1992).

Tolerance will vary with climate, soil conditions and crop varieties; these values are to be used as a guideline only.

**Table 6.10.** Landform requirement for irrigation of land with effluent

Property	Limitation			Restrictive feature
	Slight	Moderate	Severe	
Slope % for:				
Surface irrigation	<1	1–3	>3	excess runoff and erosion risk
Sprinkler irrigation	<6	6–12	>12	
Flooding	none to rare	occasional	frequent	flooding
Landform	hill crests convex side slopes and plains	concave side slopes and foot slopes	drainage plains and incised channels	erosion and seasonal waterlogging risk
Surface rock outcrop	nil	0–5%	>5%	interferes with use of cultivation, risk of runoff

Source: Hardie and Hird (1998)

Caution: these are general guidelines only, and specific site information is required to assess a particular site.

**Table 6.11.** Soil requirement table for irrigation of land with effluent

\*, ECe is saturated extract (see Section 5.9.2).

Property	Limitation			Restrictive feature
	Slight	Moderate	Severe	
Exchangeable sodium percentage	0–5	5–10	>10	structural degradation
Electrical conductivity (dS/m) (ECe)*	>4	4–8	>8	excess salt restricts plant growth
Depth to high water table (cm)	>90	45–90	<45	wetness, risk to groundwater
Depth to bedrock or hardpan (cm)	>100	50–100	<50	restricts plant growth
Hydraulic conductivity (mm/h.) (soil depth 0–100 cm)	20–80	5–20 or 80–150	<5 or >150	excess runoff, waterlogging poor filter
Available water capacity (mm/m)	>200	100–200	<100	little plant-available water in reserve
Bulk density (g/cm <sup>3</sup> )				
sandy loam	<1.8	>1.8		restricts root growth
loam and clay loam	<1.6	>1.6		
	<1.4	>1.4		
Soil pH <sub>Ca</sub> (surface layer)	>6.0	4.5–6.5	<4.5	reduces optimum plant growth
CEC (cmol(+)/kg) (average 0–50 cm)	>15	5–15	<5	unable to 'hold' plant nutrients

Source: Hird *et al.* (1996); Hardie and Hird (1998); Bond (2002).

Caution: These are only general guidelines and specific site information is required to assess a particular site.

### 6.2.3 Other factors

For the application of wastewaters that consistently contain more than 500 mg/L of TDS, such as those generated in animal feedlots or abattoirs, operators should refer to relevant guidelines outlined in ANZECC and ARMCANZ (2000c).

## 6.3 Application of biosolids to agricultural soils

### 6.3.1 General considerations

The assessment of the suitability of a site for the application of biosolids is a specialised field of expertise and account has to be taken of the biological, physical and chemical condition of the biosolids, the soil and land characteristics, and the hydrological conditions at a site. The guidelines in Tables 6.12–6.16 have taken some account of these factors, but specialised on-site advice, including hydrological advice, is required to evaluate the suitability of a site. The Environment Protection Authority of NSW, the NSW Department of Land and Water Conservation, and NSW Agriculture should be consulted for the current guidelines for the application of biosolids to agricultural land. For more information on biosolids see Huxedurp (1997).

**Table 6.12.** Properties of biosolids applied to agricultural soils

Sludge product	Total solids (%)	Expected fertiliser value on a dry weight basis	Organic matter level (%)	pH	Liming value (%)	EC dS/m
Liquid biosolids	6–12%	N 3–7%, P 0.5–4.0%	60%	6–8	nil	<4.5
Dewatered mechanical biosolids	15–25%	N 3–7%, P 0.5–4.0%	60%	6–8	nil	0.4–1.6
Lime amended biosolids	40–50%	N 0.5 to 1.5%, P 1.2%	45% (yet to be proven)	12	30%	8

Source: Huxedurp (1997)

**Table 6.13.** Soil requirements for biosolids application

Ks, hydraulic conductivity.

Property	Limitations				Restrictive features
	Slight: Class 1	Moderate: Class 2	Severe: Class 3	Very severe: Class 4	
Saturated hydraulic conductivity of most restrictive layer in top 90 cm.	Ks 2–20 mm/h. (moderately permeable soils).	Ks 0.5–2.0 mm/h. (slowly permeable soils). Ks 20–50 mm/h. (highly permeable soils).	Ks 50–100 mm/h. (very highly permeable soils).	Ks <0.5 mm/h. (very slowly permeable soils). Ks >100 mm/h. (extremely permeable soils).	Slowly and very slowly permeable soils can create a potentially anaerobic situation that can reduce plant growth, induce nitrogen loss and reduce the potential value of the applied biosolids. Increased risk of runoff. Highly to extremely permeable soils will not immobilise excess nutrients or contaminants thereby jeopardising the groundwater quality. Consider using biosolid composts.
Depth to seasonal high water table	>90 cm	60–90 cm	45–90 cm	<45 cm	Risk to groundwater from biosolids nutrients and contaminants.
Depth to bedrock or hardpan	>90 cm	60–90 cm	45–90 cm	<45 cm	Increased risk of runoff being generated after significant rainfall events. This jeopardises the quality of surface water. Where the underlying bedrock is fractured there is also an increased risk of soluble contaminants in biosolids reaching the groundwater system.
Salinity (0–45 cm)	EC <sub>e</sub> <2 dS/m Chloride precipitate not detected in silver nitrate tests.	EC <sub>e</sub> 2–4 dS/m Chloride precipitate detected (faintly) in silver nitrate test.	EC <sub>e</sub> 4–8 dS/m Chloride precipitate detected in silver nitrate test.	EC <sub>e</sub> >8 dS/m Chloride precipitate detected in silver nitrate test.	Biosolids may increase salinity. At EC <sub>e</sub> levels >4 many plant species will not grow. At EC <sub>e</sub> >8 most plant species will not grow.
Raupach pH (0–10 cm)	6.5 or greater	5.5–6.0	4.5–5.0	<4.5	Too acid. If lime amended biosolids are used, Classes 2 and 4 are not relevant. Class 4 becomes Class 3.
Minimum Raupach pH (10–45 cm)	6.0 or greater	5.0–5.5	4.0–5.0	<4.0	Too acid. If lime amended biosolids are used, Classes 2 and 4 are not relevant. Class 4 becomes Class 3.

Source: Hird *et al.* 1996.

**Table 6.14.** Landform requirements for biosolids application

Property	Limitations				Restrictive feature
	Nil or slight Class 1	Moderate Class 2	Severe Class 3	Very severe Class 4	
Slope	<8%	8–10%	10–15%	>15%	Increases risk of surface flow of water and movement of soil or biosolids downslope.
Flooding	none	rare	common	very common	Biosolids left at or near the surface may be picked up by flood waters. Consider injected liquid biosolids to overcome constraint.
Landform	hillcrests and concave side slopes	convex side slopes	foot slopes	drainage plains and incised channels	Foot slopes and drainage plains are prone to erosion and seasonal wetness.
Surface rock outcrop	nil	0–2%	2–10%	>10%	Surface rock will interfere with biosolids incorporation and damage machinery.

Source: Hird *et al.* (1996).

**Table 6.15.** Maximum allowable soil contaminant concentrations in the surface 0–75 cm for land used for food production

Contaminant	Maximum concentration (mg/kg dry weight of soil)
Arsenic	20
Cadmium	3
Chromium	100
Copper	100
Lead	150
Mercury	1
Nickel	60
Selenium	5
Zinc	200
DDT/DDD/DDE	0.5
Aldrin	0.02
Dieldrin	0.02
Chlordane	0.02
Heptachlor	0.02
Hexachlorobenzene	0.02
Lindane	0.02
BHC	0.02
PCBs	0.3

Adapted from EPA (1995).

**Table 6.16.** Land requirements for application of municipal biosolids

SAR, sodium adsorption ratio.

Property	Limitations			Restrictive features
	Slight	Moderate	Severe	
Frozen soil			ice	permafrost
Hydraulic conductivity (Ks) (minimum value 0–150 cm)	50–150 mm/h. <150 mm/h.	5–50 mm/h. 150–500 mm/h.	<5 mm/h. >500 mm/h.	potential for anaerobic conditions poor filter: risk to groundwater
Depth to high water table	>90 cm	45–90 cm	<45 cm	risk to groundwater
Slope	8%	8–15%	15%	risk to surface waters
Depth to bedrock	100 cm	50–100 cm	<50 cm	risk to surface waters
SAR* 0–50 cm	–	–	>12	excess sodium
Salinity (ECe) (mS/cm) 0–50 cm	4	4–8	8	excess salt
Flooding	none	rare	common	risk to surface waters
Bulk density (t/m <sup>3</sup> )	<1.7	<1.7	>1.7	inhibits plant root growth
Cation exchange capacity (0–50 cm)	15 cmol(+)/kg	5–15 cmol(+)/kg	<5 cmol(+)/kg	low adsorption of biosolids nutrients and heavy metals
Available water capacity (0–15 cm)	150 mm	75–150 mm	<75 mm	poor water-holding capacity

Adapted from USDA (1983).

### 6.3.2 Key references

Hart (1974); State Pollution Control Commission (1979); ANZECC (1992); Huxedurp (1997); Hardie and Hird (1998); ARMCANZ, ANZECC and NHMRC (2000).



# 7

## Heavy metal contaminants

### 7.1 Introduction

Heavy metals include the metals with higher atomic weights and are environmentally significant because many of them are essential to plant and animal growth as trace elements to maintain biological functions. Many of them can also become toxic at relatively low concentrations. Heavy metals can have naturally high levels in some soils and environments where they occur in rocks or are concentrated by natural processes. Many heavy metals actually occur in inert forms in soils and rocks and only become available to plants and animals if the environmental conditions are altered. Such alterations would result in changes in pH or the reduction of available oxygen.

A major source of heavy metals in the environment is the release and spreading of metals as a consequence of human activity including mining, industrial processes and the spreading of fertilisers. Lead is spread in older style paints and by vehicle emissions. Erosion from mine sites can cause contamination with a range of heavy metals.

Many aspects of heavy metals are discussed in Naidu *et al.* (1996).



## 7.2 Levels of heavy metals

**Table 7.1.** Average abundance (mg/kg = ppm) of total heavy metals in the earth’s crust, common minerals and in typical soils

Element	Earth’s crust	Basalt	Granite	Sandstone	Shale	Limestone	Soil range
Antimony	0.2	0.2	0.2	n/a	1	–	0.2–10.0
Arsenic	1.5–1.8	1.5–2.0	1.5–2.0	1–2	15	1.7–2.5	0.1–40.0
Bismuth	0.05–0.17	0.03–0.15	0.07–0.01	n/a	0.18	–	0.1–0.4
Cadmium	0.11–0.20	0.13–0.20	0.09–0.20	n/a	0.2	0.1	0.01–2.00
Cobalt	25	50	1–5	0.3	20	4	1–40
Chromium	100	200–220	4–20	35	100–120	10	5–1000
Copper	55	90–100	10–15	2	50	4–5	2–100
Indium	0.049	0.58	0.04	n/a			0.2–0.5
Lead	12.5–14.0	3–6	18–24	7–12	20	8–9	2–300
Manganese	950	2200	500	n/a	850	1100	850
Mercury	0.05–0.08	0.01–0.05	0.085	0.03–0.05	0.09–0.50	0.05	0.01–0.50
Molybdenum	1.5	1.0–1.5	1.4–2.0	0.2	3	1	2
Nickel	75	140–150	0.5–8.0	2	50–70	12–20	5–500
Selenium	0.05	0.05	0.05	0.05	0.6	0.08	0.01–1.20
Thallium	0.45–0.60	0.08–0.10	0.75–1.10	0.82	0.3	–	0.1–0.8
Zinc	70	100–110	40	16	100	20–25	20

Source: Plant and Raiswell (1983).

**Table 7.2.** Examples of inputs of toxic heavy metals into the atmosphere from natural sources and industrial emissionsng, nanograms; ng/kg =  $10^{-9}$  g/kg = 0.001 ppm

Source	Arsenic	Cadmium	Lead	Mercury	Selenium
<b>Natural inputs</b>					
Volcanic (ng/kg dust)	300–800	30–800	100–9600	n/a	10–1700
mg/kg	0.30–0.80	0.03–0.80	0.10–9.60		0.010–1.700
Windblown (ng/kg dust)	0.5–2.0	0.002–1.700	0.4–70.0	n/a	0.6000–
mg/kg	0.0005–0.0020	0.000002– 0.001700	0.0004–0.0700		0.0006
<b>Forest fires</b>					
(mg/kg dust)	0.5–4.4	0.03–2.00	1.1–78.0	n/a	–
Vegetation (ng/kg dust)	3.5000	2.7–36.0	21–280	n/a	–
mg/kg	0.0035	0.0027–0.0360	0.021–0.280		
Sea spray (ng/kg)	0.1–0.6	0.001–0.003	0.001–0.090	n/a	–
mg/kg	0.0001–0.0006	0.000001– 0.000003	0.000001– 0.000009		
<b>European emissions (1979)</b>					
Coal combustion (t/year)	461	146	1676	221	–
Oil combustion (t/year)	217	110	1159	–	–

Source: Pacyna (1987), and Fergusson (1990).

**Table 7.3.** Examples ( $\times 10^3$  t/y) of heavy metal production and recent global emissions to soils

\*, data from Chilvers and Peterson (1987).

Heavy metal	Year			Global emissions to soil, 1980s
	1930	1950	1980–1985	
Cadmium	1.3	6	15–19	22
Chromium	560	2270	11 248–9940	896
Copper	1611	2650	7660–8114	954
Lead	1696	1670	3580*	796
Manganese	3491	5800	26 720	1670
Mercury	3.8	4.9	7.1–6.8	8.3
Nickel	22	144	759–778	325
Tin	179	172	251–194	–
Zinc	1394	1970	5229–6024	1372

Source: Alloway (1990).

**Table 7.4.** Background levels of heavy metals in Australian soils (adapted from ANZECC and ARMCANZ (2000c))

nd, no data.

Metal	Olszowy <i>et al.</i> (1995)			Barry (1997)			Tiller (1983)	
	Range mg/kg	Mean mg/kg	Median mg/kg	Range mg/kg	Mean mg/kg	Median mg/kg	Range mg/kg	Mean mg/kg
Al	nd			nd			nd	
As	5–53	7	5	1–20	3	3	nd	
B*	0.09–8.00	0.87	0.61	nd			nd	
Cd	nd			0.016–2.000	0.195	0.125	nd	
Cr	5–56	8	5	<9–573	132	65	nd	
Co	nd			<6–165	37	26	<2–170	11
Cu	3–412	16	9	<8–148	43	38	<1–190	22
Fe	nd			nd			nd	
Pb	5–56	14	14	5–81	27	24	nd	
Li	nd			nd			nd	
Mn	4–7357	814	201	nd			4–5100	780
Hg	nd			<0.006–0.150	0.042	0.035	nd	
Mo	nd			0.2–5.2	1.34	1.01	<1–20	3.2
Ni	5–38	6	5	<10–439	88	27	nd	
Se	nd			<0.05–3.20	0.37	0.28	nd	
U	nd			nd			nd	
V	5–121	21	12	nd			nd	
Zn	5–92	21	10	<12–263	76	73	<2–180	34

Source: Spouncer and Mowat (1991a–d)

Table 7.5. Relative contents of elements in the crust and soils (after Sposito 1989)

Element	Element content in soil mg/kg	Element content in crust mg/kg	Enrichment factor Soil content/crust content	Element	Element content in soil mg/kg	Element content in crust mg/kg	Enrichment factor Soil content/crust content
<b>Elements that are strongly enriched in soils</b>				<b>Elements that show weak depletion in soils</b>			
Carbon	25 000	480	52	Sodium	12 000	23 000	0.52
Nitrogen	2000	25	80	Chlorine	100	130	0.77
<b>Elements that show some enrichment in soils</b>				Potassium	15 000	21 000	0.71
Fluorine	950	430	2.2	Calcium	24 000	41 000	0.59
Boron	33	10	3.3	Scandium	8.9	16	0.56
Sulfur	1600	260	6.2	Titanium	2900	5600	0.52
Arsenic	7.2	1.5	4.8	Vanadium	80	160	0.50
Selenium	0.39	0.05	7.8	Chromium	54	100	0.54
Bromine	0.85	0.37	2.3	Manganese	550	950	0.58
Cadmium	0.35	0.11	3.2	Iron	26 000	41 000	0.63
Antimony	0.66	0.20	3.3	Copper	25	50	0.50
Iodine	1.2	0.14	8.6	Germanium	1.2	1.8	0.67
<b>Elements that have constant concentration</b>				Rubidium	67	90	0.74
Zinc	60	75	0.80	Strontium	240	370	0.65
Gallium	17	18	0.94	Niobium	11	20	0.55
Yttrium	25	30	0.83	Molybdenum	0.97	1.5	0.65
Lithium	24	20	1.2	Silver	0.05	0.07	0.71
Oxygen	490 000	474 000	1.0	Tin	1.3	2.2	0.59
Aluminium	72 000	82 000	0.88	Thorium	9.4	12	0.78
Silicon	310 000	277 000	1.1	<b>Elements that show strong depletion in soils</b>			
Zirconium	230	190	1.2	Beryllium	0.92	2.6	0.35
Caesium	4.0	3.0	1.3	Magnesium	9000	23 000	0.39
Barium	580	500	1.2	Phosphorus	430	1000	0.43
Lanthanum	37	32	1.2	Nickel	19	80	0.24
Mercury	0.09	0.05	1.8	Cobalt	9.1	20	0.46
Lead	19	14	1.4				
Neodymium	46	38	1.2				
Uranium	2.7	2.4	1.1				

**Table 7.6.** Examples of typical ranges (mg/kg) for heavy metal contaminants in fertilisers, sewage sludge and farmyard manure

Metal	Fertiliser		Sewage sludge	Farmyard manure	Composted refuse
	Phosphate	Nitrate			
Arsenic	2–1200	2–120	3–30	3–25	2–50
Cadmium	0.1–170.0	0.05–8.50	<1–3400	0.1–0.8	0.1–100.0
Chromium	66–245	3–19	8–41 000	1–55	1.8–410.0
Cobalt	1–12	5–12	1–260	0.3–24	–
Copper	1–300	–	50–8000	2–172	13–3580
Lead	7–225	2–27	29–3600	1.1–27.0	1.3–2240
Manganese	40–2000	–	60–3900	30–970	–
Mercury	0.01–1.20	0.3–2.9	0.1–55.0	0.01–0.36	0.09–21.00
Molybdenum	0.1–60.0	1–7	1–40	0.05–3.00	–
Nickel	7–38	7–34	6–5300	2–30	1–280
Selenium	0.5–25.0	–	1–10	2.4	–
Zinc	50–1450	1–42	90–49 000	15–566	82–5894

Source: Alloway (1990).

**Table 7.7.** Key metabolic factors following environmental exposure to heavy metals

\*, individuals who have a low iron store or who are on a calcium deficient diet may absorb as much as 20% (WHO 1985). This is an example that shows the values for absorption of heavy metals can vary widely for a variety of reasons.

Factor	Lead	Mercury	Cadmium	Arsenic
Key entry pathway	ingestion, inhalation	ingestion, inhalation of metal vapour	ingestion, inhalation; e.g. tobacco	ingestion
Gastrointestinal absorption (%)	approx. 10	approx. 80 of vapour; 7 of ingested Hg <sup>2+</sup>	approx. 5*	>80
Organs accumulating	bone, teeth	kidneys, brain, liver	kidney, liver	keratinous tissue
Major routes of excretion	urine (75–80%)	urine and faeces	urine	urine
Biological half-life	approx. 20 years	approx. 35–90 days	>10 years	10–30 hours
Acute toxic effects in humans	neurological and other central nervous system and gastro-intestinal disturbances	Internal: damage to intestines, renal failure, circulatory collapse Inhalation: bronchial irritation, pneumonitis	Internal: gastro-intestinal disturbance Inhalation: chemical pneumonitis	edema, gastro-irritation, muscle spasms, coma
Chronic toxic effects in humans	impaired fertility, chromosomal abnormalities, kidney damage	inflammation of mouth, tremors, irritability, anxiety, shyness, skin lesions	renal dysfunction, bone-changes, tumours	fatigue, skin damage, non-cirrhotic portal hypertension
Provisional tolerable weekly intake (mg/kg of body weight)	Adults: 0.05 Children: 0.025 (from WHO 1989; Imray and Langley 1999)	0.0033 (organic mercury) (from WHO 1989; Imray and Langley 1999)	0.007 (from WHO 1989; Imray and Langley 1999)	0.015 (inorganic arsenic) (from WHO 1989; Imray and Langley 1999)

Adapted from Hutton (1987) and Rayment (1991).

## 7.3 Key references

Plant and Raiswell (1983); Pacyna (1987); WHO (1989); Alloway (1990); Fergusson (1990); Rayment (1991); Imray and Langley (1999).

Detailed explanations of soil testing procedures and interpretation of results are available in Peverill *et al.* (1999) for the following heavy metals: copper, zinc, manganese, iron, molybdenum, boron, cobalt and selenium.

## 7.4 Further reading

Naidu *et al.* (1996).



# 8

## Units and conversions

### 8.1 SI units

Wherever possible, SI units have been used; however, these are not always the most convenient or useful (see Table 8.1).

Table 8.1. SI units

Quantity	Unit	Symbol	Equivalent
Length	metre	m	–
Mass	kilogram	kg	–
Time	second	s	–
Amount of substance	Mole	mol	–
<i>Derived units</i>			
Force	newton	N	kg m/s <sup>2</sup>
Work or energy	joule	J	Nm
Pressure	1 newton/m <sup>2</sup>	N/m <sup>2</sup>	1 Pascal (Pa)
Concentration	Mole per cubic metre	mol/m <sup>3</sup>	
Concentration	Mole per litre	mol/L	M
Density	kilogram per cubic metre	kg/m <sup>3</sup>	

### 8.2 Other units and conversions

#### 8.2.1 Relative amounts – proportions

Relative proportions or amounts are commonly used in soil testing. These are usually expressed as follows:

- percentages (%) = g/100 g



**Table 8.2.** Prefixes for units

Fraction	Prefix	Symbol	Multiple	Prefix of multiple	Symbol of multiple
$10^{-1}$	deci	d	10	deca	da
$10^{-2}$	centi	c	$10^2$	hecto	h
$10^{-3}$	milli	m	$10^3$	kilo	k
$10^{-6}$	micro	$\mu$	$10^6$	mega	M
$10^{-9}$	nano	n	$10^9$	giga	G
$10^{-12}$	pico	p	$10^{12}$	tera	T

Adapted from Sposito (1989).

- 1 nanogram (ng) =  $10^{-9}$  g
- 1 milliequivalent = 1 millimole of charge = mole of charge/1000
- $\mu\text{g/L}$  = microgram/L =  $10^{-6}$  g/L
- ng = nanogram =  $10^{-9}$  g

### 8.2.2 Soil particle sizes and pore sizes

Soil particle sizes are usually expressed as:

- mm = 0.001 m = 1000 micrometre ( $\mu\text{m}$ )

### 8.2.3 Bulk density – specific gravity – air porosity

- Bulk density or specific gravity:  $\text{g/cm}^3 = 1000 \text{ kg/m}^3 = \text{t/m}^3$
- Air porosity (%) =  $\text{cm}^3$  of air per  $\text{cm}^3$  of soil

### 8.2.4 Soil strength/pressure

- soil strength: MPa = 1000 kPa
- 1 Newton/ $\text{m}^2$  = 1 Pa
- 1000 Pa = 1 kPa

**Table 8.3.** Other units used and SI equivalents

Quantity	Unit	Symbol	Equivalent
Length	millimetre	mm	0.001 m
	centimetre	cm	0.01 m
Mass	gram	g	0.001 kg
	tonne	t	1000 kg
Time	year	yr	$\approx 3.18 \times 10^7$ s
	minute	min.	60 s
	hour	h.	3600 s
	day	d.	$8.64 \times 10^4$ s
Area	hectare	ha	$10^4 \text{ m}^2$
Concentration	mole/L	mol/L	$1000 \text{ mol/m}^3$

- 1 kPa = 0.145 pounds per square inch
- 1 t/m<sup>2</sup> on the ground surface = 1000 kg/m<sup>2</sup> under the force of gravity = 1000 × 9.80665 Pa = 9.80665 kPa (based on gravitational acceleration)

### 8.2.5 Soil erodibility

- soil flux for wind erosion: g/m/s. = 0.001 kg/m/s
- erosion rate for wind erosion: kg/ha/min. =  $6 \times 10^5$  kg/m<sup>2</sup>/s
- rainfall erosivity: MJ. mm/(ha.h.yr)
- soil erodibility: t/ha.yr per unit of rainfall erosivity

### 8.2.6 Daily evaporation rates

- evaporation rate: mm/d

### 8.2.7 Water-holding properties

- relative amounts of water: % = g/100 g (gravimetric) or cm<sup>3</sup>/100 cm<sup>3</sup> (volumetric)
- for a one-dimensional scale in soils (usually depth), cm<sup>3</sup>/100 cm<sup>3</sup> converts to cm of water per 100 cm of soil or mm of water per cm of soil or mm of water per m of soil
- total amounts of water: mm = 0.001 m
- bulk density: g/cm<sup>3</sup> = 1000 kg/m<sup>3</sup> = 1 t/m<sup>3</sup>
- moisture potential: kPa = J/kg = 10 cm = 0.15 pounds per square inch

### 8.2.8 Chemical concentrations (liquid)

#### (a) Weight base

1 part per million (ppm) = 1 mg/kg = 1 mg/L for water (20°C) ~ 1 mg/L for salt water and seawater.

Note:

- density of water at 20°C = 0.998 g/mL
- density of seawater at 20°C = 1.025 g/mL

#### (b) Molarity base

##### (i) Quantity

One mole is a standard number of atoms and relates to the chemical activity of a substance, which is why it is widely used. It is equal to the quantity of the substance that has a weight in grams equal to the atomic or molecular weight of the substance. The molecular weight equals the sum of the atomic weights that make up the molecule under consideration. The number of molecules or atoms in a mole is the same for all substances, approximately  $6.0221367 \times 10^{23}$ , which is Avogadro's Number. The atom carbon-12 is used as the standard. Thus a mole of carbon-12 atoms has a mass of 12 g. However, the actual atomic weight of carbon is 12.011 g because of the natural occurrence of small amounts of the isotopes carbon-14 and carbon-13. Atomic weights

are not always whole numbers because of the occurrence of isotopes. See Table 8.4 for a listing of atomic weights of commonly encountered elements.

- 1 mole = atomic weight or molecular weight (MWt) of element or compound
- 1 Molar is used to describe the amount of a substance in solution:  
1 molar = 1 mole per litre = 1 M
- 1 millimolar (mM) = 1 millimole per litre = 0.001 mole/L = 0.001M
- 1 centimole (cmole) = 0.01 mole

(ii) *Charge*

- a milliequivalent (mequiv.) = mmol of ion  $\times$  charge of ion
- a milliequivalent per litre = mmol/L  $\times$  charge

(iii) *For aqueous solutions conversion of ppm to milliequivalent per litre*

1 ppm = (charge of ion/molecular weight)  $\times 10^{-3}$  milliequivalent per litre

- for Ca: 1 ppm =  $4.99 \times 10^{-5}$  milliequivalent per litre
- for Mg: 1 ppm =  $8.23 \times 10^{-5}$  milliequivalent per litre
- for Na: 1 ppm =  $4.35 \times 10^{-5}$  milliequivalent per litre
- for K: 1 ppm =  $2.56 \times 10^{-5}$  milliequivalent per litre
- for Cl: 1 ppm =  $2.82 \times 10^{-5}$  milliequivalent per litre
- for  $\text{SO}_4^{2-}$ : 1 ppm =  $2.08 \times 10^{-5}$  milliequivalent per litre

**Table 8.4.** Atomic weights of commonly encountered elements (Brescia *et al.* 1967)

Element	Atomic weight = 1 mole of atoms (g)	Element	Atomic weight = 1 mole of atoms (g)	Element	Atomic weight = 1 mole of atoms (g)
Aluminium	26.98	Gold	196.97	Platinum	195.09
Antimony	121.75	Helium	4.00	Potassium	39.10
Argon	39.95	Hydrogen	1.01	Selenium	78.96
Arsenic	74.92	Iodine	126.90	Silicon	28.09
Barium	137.34	Iron	55.85	Silver	107.87
Bismuth	208.98	Lead	207.19	Sodium	22.99
Boron	10.81	Lithium	6.94	Strontium	87.62
Bromine	79.91	Magnesium	24.31	Sulfur	32.06
Cadmium	112.40	Manganese	54.94	Thorium	232.04
Calcium	40.08	Mercury	200.59	Tin	118.69
Carbon	12.01	Molybdenum	95.94	Tungsten	183.85
Caesium	132.91	Neon	20.18	Uranium	238.03
Chlorine	35.45	Nickel	58.71	Vanadium	50.94
Chromium	52.00	Niobium	92.91	Zinc	65.37
Cobalt	58.93	Nitrogen	14.01		
Copper	63.54	Oxygen	16.00		
Fluorine	19.00	Phosphorus	30.97		

### 8.2.9 Level of exchangeable cations – cation exchange capacity

#### (a) Units

1 cmol (+)/kg = 1 milliequivalent per 100 g of soil

#### (b) Conversions

##### (i) cmol(+)/kg to t/ha of element

$$1 \text{ cmol (+) / kg} = \frac{0.001 \times \text{MWt} \times D \times \text{BD t/ha}}{C}$$

Where C is the charge of the cation or anion; MWt is the molecular weight of the element in g; D is the depth of the soil in cm; BD is the bulk density of the soil in g/cm<sup>3</sup> (assumed to be 1.40 g/cm<sup>3</sup> for these calculations).

- for Na: 1 cmol(+)/kg = 0.32 t/ha for 0–10 cm
- for Na: 1 cmol(+)/kg = 0.48 t/ha for 0–15 cm
- for Ca: 1 cmol(+)/kg = 0.28 t/ha for 0–10 cm
- for Ca: 1 cmol(+)/kg = 0.42 t/ha for 0–15 cm
- for Mg: 1 cmol(+)/kg = 0.17 t/ha for 0–10 cm
- for Mg: 1 cmol(+)/kg = 0.26 t/ha for 0–15 cm
- for K: 1 cmol(+)/kg = 0.55 t/ha for 0–10 cm
- for K: 1 cmol(+)/kg = 0.82 t/ha for 0–15 cm

##### (ii) t/ha of element to cmol(+)/kg

- for Na: 1 t/ha = 3.11 cmol(+)/kg for 0–10 cm
- for Na: 1 t/ha = 2.07 cmol(+)/kg for 0–15 cm
- for Ca: 1 t/ha = 3.56 cmol(+)/kg for 0–10 cm
- for Ca: 1 t/ha = 2.38 cmol(+)/kg for 0–15 cm
- for Mg: 1 t/ha = 5.87 cmol(+)/kg for 0–10 cm
- for Mg: 1 t/ha = 3.92 cmol(+)/kg for 0–15 cm
- for K: 1 t/ha = 1.83 cmol(+)/kg for 0–10 cm
- for K: 1 t/ha = 1.22 cmol(+)/kg for 0–15 cm

##### (iii) 1 t/ha of gypsum will add the following amounts of Ca to the soil in cmol(+)/kg of soil (assuming gypsum is 20% Ca and 100% dissolution)

- for Ca: 1 t/ha of gypsum = 1.43 cmol(+)/kg of Ca for 0–5 cm
- for Ca: 1 t/ha of gypsum = 0.71 cmol(+)/kg of Ca for 0–10 cm
- for Ca: 1 t/ha of gypsum = 0.48 cmol(+)/kg of Ca for 0–15 cm

##### (iv) 1 t/ha of lime (CaCO<sub>3</sub>) will add the following amounts of Ca to the soils in cmol(+)/kg of soil (assuming lime is 40% Ca and 100% dissolution)

- 1 t/ha of lime = 2.86 cmol(+)/kg of Ca for 0–5 cm
- 1 t/ha of lime = 1.42 cmol(+)/kg of Ca for 0–10 cm
- 1 t/ha of lime = 0.96 cmol(+)/kg of Ca for 0–15 cm

### 8.2.10 Salinity

- $\text{dS/m} = \text{mS/cm} = \text{mmho/cm} = \text{concentration of salt (mg/L)} = 640 \times \text{EC}$

However, to convert EC1:5 to Total Soluble Salts (TSS) in the soil:

$$\text{EC1:5} = \text{TSS}/0.32 \text{ where TSS is in g/100 g}$$

(See Section 5.9.)

### 8.2.11 Fertiliser and lime rates

- 1 pound per acre = 1.12 kg/ha
- 1 kg/ha = 0.893 pound per acre
- 1 ton per acre = 2.509 tonne per hectare
- 1 tonne per hectare = 0.399 ton per acre

### 8.2.12 Acres and hectares

- 1 acre = 0.405 hectare
- 1 ha = 100 m  $\times$  100 m = 10<sup>4</sup> m<sup>2</sup>

### 8.2.13 Yields of crops

Table 8.5. Yields of crops

Crop	Pounds per bushel	Kilograms per bushel (UK and Australia)	Kilograms per bag	1 bag per acre converted to t/ha	1 t/ha converted to bags/acre	20 bags per acre converted to t/ha
Wheat	60	27.22	81.65	0.202	4.98	4.03
Barley	50	22.68	68.04	0.168	5.95	3.36
Lupins	60	27.22	81.65	0.202	4.96	4.03
Oats	40	18.14	54.43	0.134	7.44	2.69
Canola	56	25.40	76.20	0.188	5.32	3.76
Peas	60	27.22	81.65	0.202	4.96	4.03
Sorghum	60	27.22	81.65	0.202	4.96	4.03
Rice	43	19.50	58.50	0.144	6.92	2.89
Sunflower	25	11.34	34.02	0.084	11.91	1.68
Vetches	60	27.22	81.65	0.202	4.96	4.03

Source: Collins (1966), and Weast (1974).

These conversions are based on the following:

1 pound = 0.45359 kg

1 bag = 3 bushels

1 bushel = 2219.354 cubic inches or 36.375 L

1 acre = 0.405 ha

(The imperial or British bushel dating from 1824 is 36.375 L, but the US bushel dating from 1912 is 45.935 L.)

# General reading

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